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IEEE 3004 STANDARDS:
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IEEE Std 3004.8™-2016

Recommended Practice for Motor Protection in Industrial and Commercial Power Systems

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IEEE Recommended Practice for Motor Protection in Industrial and Commercial Power Systems

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IEEE Industry Applications Society

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IEEE-SA Standards Board

Abstract: The protection of motors used in industrial and commercial power systems is covered. It is likely to be of greatest value to the power-oriented engineer with limited experience in the area of protection and control. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

Keywords: coordination, IEEE 3004.8, induction motors, inverse-time overcurrent element, motor protection, motor protection relay, negative sequence characteristics, overcurrent protection, permanent magnet motors, relay protection, resistive temperature detector, rotors, rotor thermal protection, stators, stator thermal protection, synchronous motors, temperature detector voting, temperature sensors, thermal model overload protection, unbalanced protection

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Rasheek Rifaat, *Chair*
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Ed Larsen
Claudio Mardegan
Chuck Mozina
Dan Neeser
Lorraine Padden
Louie Powell
Daniel Ransom
Marcelo E. Valdes

At the time this IEEE recommended practice was completed, the IEEE 3004.8 Project Working Group had the following membership:

Rasheek Rifaat, *Working Group Committee Chair*
Lorraine K. Padden, *Project Working Group Chair*

Partha Basu
Thomas Beckwith
Sirak Belayneh
Robert David Bredhold
James Bryan
Jim Crook
Randall Groves
Jeffrey Hensley
Chris Heron
Byron Hohrein
Umar Khan
John Kay
Daniel Leland Ransom
Bill Stewart

The following individuals contributed to the development of this recommended practice, but were not working group members at the time this recommended practice was completed:

Smit Bavishi
Paul Cardinal
Jerry Franklin
David Hinchliffe
Mayank Jain
Ed Larsen
Duane Leschert
Daniel Neeser
Timothy O'Hearn
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David C. Rains†
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Thomas Beckwith
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Introduction

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When this project is completed, the technical material in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Standby Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3004.8

A general update was made to the material from Chapter 10 of the *IEEE Buff Book*™. Material added or expanded includes details for reduced-voltage motor starting, recommended protection functions using multifunction motor protection relays for contactor controlled fused starters and breaker controlled starters, along with single-line and three-line diagrams, adjustable speed drive applications, dc motor protection, motor bus transfer, partial discharge monitoring, and a detailed example of motor protection using a multifunction motor protection relay.

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1. Scope

This recommended practice covers the protection of motors used in industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in the area of protection and control. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

API Std 541, Form-Wound Squirrel Cage Induction Motors—500 Horsepower and Larger, 5th Edition.[1]

API Std 546, Brushless Synchronous Machines—500 kVA and Larger, 3rd Edition.

API Std 547, General-Purpose Form-Wound Squirrel Cage Induction Motors—250 Horsepower and Larger, 1st Edition.

IEEE Std 43™, IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery.[2,3]

IEEE Std 112™, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators.

IEEE Std 115™, IEEE Guide for Test Procedures for Synchronous Machines Part I—Acceptance and Performance Testing Part II—Test Procedures and Parameter Determination for Dynamic Analysis.

IEEE Std 141™-1993 (Reaff 1999), IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book*™).

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IEEE Std 241™-1990 (Reaff 1997), IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (*IEEE Gray Book*™).

IEEE Std 242™-2001, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book*™).

IEEE Std 519™, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

IEEE Std 620™, IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines.

IEEE Std 841™, IEEE Standard for Petroleum and Chemical Industry—Premium Efficiency, Severe-Duty, Totally Enclosed Fan-Cooled (TEFC) Squirrel Cage Induction Motors—Up to and Including 370 kW (500 hp).

IEEE Std 1015™-2006, IEEE Recommended Practice for Applying Low-Voltage Circuit Breakers Used in Industrial and Commercial Power Systems (*IEEE Blue Book*™).

IEEE Std 1349™, IEEE Guide for the Application of Electric Motors in Class I, Division 2 and Class I, Zone 2 Hazardous (Classified) Locations.

IEEE Std 1683™, IEEE Guide for Motor Control Centers Rated up to and including 600 V AC or 1000 V DC with Recommendations Intended to Help Reduce Electrical Hazards.

IEEE Std 3001.5™, IEEE Recommended Practice for the Application of Power Distribution Apparatus in Industrial and Commercial Power Systems.

IEEE Std 3001.8™, IEEE Recommended Practice for the Instrumentation and Metering of Industrial and Commercial Power Systems.

IEEE P3001.11 D8, IEEE Draft Recommended Practice for Application of Controllers and Automation to Industrial and Commercial Power Systems.[4]

IEEE Std 3003.2™, IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems.

IEEE Std 3004.1™, IEEE Recommended Practice for the Application of Instrument Transformers in Industrial and Commercial Power Systems.

IEEE Std 3004.5™, IEEE Recommended Practice for the Application of Low-Voltage Circuit Breakers in Industrial and Commercial Power Systems.

IEEE Std 3006.5™, IEEE Recommended Practice for the Use of Probability Methods for Conducting a Reliability Analysis of Industrial and Commercial Power Systems.

IEEE Std 3006.7™, IEEE Recommended Practice for Determining the Reliability of 7×24 Continuous Power Systems in Industrial and Commercial Facilities.

IEEE Std 3006.9™, IEEE Recommended Practice for Collecting Data for Use in Reliability, Availability, and Maintainability Assessments of Industrial and Commercial Power Systems.

[4]Numbers preceded by P are IEEE authorized standards projects that were not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining drafts, contact the IEEE.

IEEE Std 3007.1™, IEEE Recommended Practice for the Operation and Management of Industrial and Commercial Power Systems.

IEEE Std 3007.2™, IEEE Recommended Practice for the Maintenance of Industrial and Commercial Power Systems.

IEEE Std 3007.3™, IEEE Recommended Practice for Electrical Safety in Industrial and Commercial Power Systems.

IEEE Std C37.06™, IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V.

IEEE Std C37.2™, IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.

IEEE Std C37.13™, IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.

IEEE Std C37.14™, IEEE Standard for DC (3200 V and below) Power Circuit Breakers Used in Enclosures.

IEEE Std C37.17™, IEEE Standard for Trip Systems for Low-Voltage (1000 V and below) and AC and General Purpose (1500 V and below) DC Power Circuit Breakers.

IEEE Std C37.46™, IEEE Specifications for High-Voltage (>1000 V) Expulsion and Current-Limiting Power Class Fuses and Fuse Disconnecting Switches.

IEEE Std C37.96™-2012, IEEE Guide for AC Motor Protection.

IEEE Std C37.110™, IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes.

IEEE Std C62.21™, IEEE Guide for the Application of Surge Voltage Protective Equipment on AC Rotating Machinery 1000 V and Greater.

NEMA ICS 2, Industrial Control and Systems Controllers, Contactors and Overload Relays Rated 600 Volts.[5]

NEMA MG 1-2011, Motors and Generators.

NFPA 20-2013, Standard for the Installation of Stationary Pumps for Fire Protection.[6]

NFPA 70-2014, National Electrical Code® (NEC®).

UL 347, UL Standard for Safety Medium-Voltage AC Contactors, Controllers, and Control Centers.[7]

UL 845, UL Standard for Motor Control Centers.

[5]NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (http://global.ihs.com/).
[6]NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (http://www.nfpa.org/).
[7]UL standards are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (http://www.global.ihs.com/).

3. Definitions, abbreviations, and acronyms

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms and Definitions* should be referenced for terms not defined in this clause.[8]

3.1 Definitions

abnormal operating condition: As applied to motors, including, but not limited to, starting, locked rotor, voltage unbalance, overload, and short-circuit. As applied to equipment in classified locations, equipment failure is considered to be an abnormal operating condition.

accelerating thermal limit (loci): The time-current relationship limit based on allowable temperature limit of the rotor during the accelerating (starting) process.

accelerating time-current curve: The characteristic starting current versus time curve representing the motor acceleration at a given applied voltage.

adjustable speed drive: An electric drive designed to provide easily-operable means for speed adjustment of the motor, within a specified speed range.

ambient temperature: Ambient temperature is the temperature of the surrounding cooling medium, such as gas or liquid, which comes into contact with the heated parts of the apparatus. (See NEMA MG-1.)[9]

approved: Acceptable to the authority having jurisdiction. (See NFPA 70, National Electrical Code.)

arc flash detector (AFD): A device/function that detects an unintentional electrical arc in air.

autoignition temperature (AIT): The minimum temperature required to initiate or cause self-sustained combustion of a solid, liquid, or gas independently of the heating or heated element. (See NFPA 497-2008 [B47].)[10]

authority having jurisdiction (AHJ): An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure. (See NFPA 70, National Electrical Code.)

basic impulse insulation level (BIL): A reference impulse insulation strength expressed in terms of the crest value of withstand voltage of standard full impulse voltage wave.

bypass contactor: A contactor that is connected in parallel with the drive system or reduced-voltage starter so as to effectively take the drive system or reduced-voltage equipment out of the circuit, allowing the machine to run (after starting) in across-the-line mode.

NOTE—Bypass contactors are often used with drive systems. There are two reasons for bypass. The most common is for maintenance purposes. If the drive is out for maintenance, the bypass contactor is closed to allow the motor to run across-the-line (ATL). The second reason is to allow the drive to bring one motor to full speed, then bypass the drive after coming to full speed and switch to another motor. This allows the user to have one drive for many motors. Adjustable speed drive (ASD) applications also require an isolation contactor on ASD output to prevent the ASD from being in parallel with the bypass contactor.[11]

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[8]IEEE Standards Dictionary Online subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.
[9]Information on references can be found in Clause 2.
[10]The numbers in brackets correspond to those of the bibliography in Annex A.
[11]Notes to text, tables, and figures are for information only and do not contain requirements needed to implement the standard.

Class B rise: Based on a maximum 40 °C ambient, a motor stator temperature rise at 1.0 service factor of 80 °C (measured by resistance) or 80 °C, 85 °C, or 90 °C (measured by embedded detectors) in accordance with NEMA MG-1 depending on the motor size, motor type, enclosure type, and voltage rating. The rise at 1.0 service factor corresponds to Class B type of insulation system in the NEMA MG-1 temperature rise tables.

clear space (CS): Clear space time margin between time current characteristic curves; and if applicable, the upstream fuse minimum melting curve is adjusted for preload.

closed-transition transfer (parallel transfer): A motor bus transfer (MBT) designed to close the new source breaker before tripping the old source breaker with the result that both source breakers are closed briefly at the same time during the transfer process.

common-mode voltage (CMV): In the context of adjustable speed drives (ASDs), common-mode voltage is the displacement of the neutral point (and each phase voltage) of the ASD output from ground due to the switching of the solid-state devices in the drive. It is an alternating voltage whose magnitude and frequency components are dependent on the drive topology.

NOTE—All present drive topologies create CMV to some extent. CMV can also be created at the motor if phase circuit conductors, unsymmetrical with respect to the equipment grounding conductor(s) or grounded sheaths or raceways, are used between the ASD output and the motor.

continuous duty: Operation at a substantially constant load for an indefinitely long time. This is also known as continuous rating in NEMA MG-1.

corona: A type of localized discharge resulting from transient gaseous ionization on an insulation system when the voltage stress exceeds a critical value. The ionization is usually localized over a portion of the distance between the electrodes of the system. (Corona activity can result in surface discharges and surface tracking on motor windings.) Corona is visible partial discharges in gases adjacent to a conductor. (See IEEE Std 1434™ [B29].)

current-limiting (CL) fuse: A fuse that limits the peak-let-through current to less than the prospective current. CL fuses are used on low-voltage and medium-voltage motors as primary fault protection device and on some small motors as fault and overload protection devices.

explosionproof equipment: Equipment enclosed in a case that is capable of withstanding an explosion of a specified gas or vapor that may occur within it and of preventing the ignition of a specified gas or vapor surrounding the enclosure by sparks, flashes, or explosion of the gas or vapor within, and that operates at such an external temperature that a surrounding flammable atmosphere will not be ignited thereby. (See NFPA 70, National Electrical Code.)

exposed surface: A surface that is internal to an enclosure or an external surface of an enclosure which could be exposed to the surrounding flammable atmosphere, without the benefit of an enclosure that would contain an explosion or exclude the hazardous gas. (An exposed internal surface may be the rotor, stator, or space heater surfaces of open and totally enclosed fan-cooled [TEFC] motors. An exposed external surface is the exterior surface, which could be exposed to the surrounding flammable atmosphere such as the exterior surface of explosionproof, pressurized, or force ventilated enclosures.)

fast transfer–supervised: An open-transition method wherein the close is supervised to check that the voltage phase angle difference between the motor bus voltage and the new source voltage is within a predetermined acceptable limit.

fast transfer–unsupervised: An open-transition method wherein the close is implemented without a sync-check device or implemented with sync-check relays with performance and response time which may be inadequate.

field winding: The rotor circuit on an ac synchronous motor, which consists of winding connected to a dc source and produces the main electromagnetic field of the motor.

NOTE—It is rare, but there are times when the field winding is stationary. This occurs mostly with brushless exciters.

high-inertia load: A load that has a moment of inertia that exceeds normal values, as described in NEMA MG-1, and for which the motor needs to be designed to have both thermal and mechanical capability to accelerate the load to operating speed without exceeding its limits. (See NEMA MG-1-2011 Table 12 through Table 7, 20–1, and 21–6.)

harmonic: A sinusoidal component of a periodic wave or quantity having any frequency within the spectra. There are three basic classes of harmonics: frequencies with an integer multiple of the fundamental frequency, frequencies with a non-integer multiple of the fundamental frequency (inter-harmonics), and frequencies that are below the fundamental frequency (sub-harmonics).

identified (as applied to equipment): Recognizable as suitable for the specific purpose, function, use, environment, application, and so forth, where described in a particular *Code* requirement. (See NFPA 70, National Electrical Code.)

IC Code: The IC Code designates the method of electrical machine cooling as described in NEMA MG-1, Part 6.

IP Code: The IP Code designates the degree of protection provided by the enclosure of a rotating machine as described in NEMA MG-1, Part 5.

in-phase transfer: An open-transition method wherein the close command to the new breaker occurs at a phase angle in advance of phase coincidence between the motor bus and the new source to compensate for the new breaker's closing time.

listed: Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of products or services, that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services, and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose. (See NFPA 70®, National Electrical Code.)

locked rotor thermal limit (permissible locked rotor time): The maximum permissible safe time versus locked rotor current flowing in the windings at rated voltage and frequency.

locked rotor torque: The minimum torque that a motor will develop at rest, for all angular positions of the rotor, at rated voltage and frequency.

loss of synchronism (out of step): A condition that exists when the synchronous machine has lost synchronism with respect to the supply system.

motor bus: An auxiliary system bus that primarily supplies power to motor loads.

motor bus transfer (MBT): The process of transferring motor bus loads from one power source to another source.

multisection motor: A motor whose construction utilizes a component block approach in the assembly of the enclosure, that is, the enclosure has a number of bolted joints which could connect together the stator frame, the ventilation hood, the motor base, the bearing supports, and enclosure covers.

NEMA Frame: This refers to the NEMA MG-1 system of a standardized frame designation for AC machines including 449 frame size and smaller. NEMA MG-1-2011, Part 4 provides critical mounting dimensions for each frame size.

normal operating condition: As applied to motors, a normal operating condition is operating at rated full load steady state conditions. (See NFPA 70, National Electrical Code, Section 500.8(B)(5).) Locked rotor, starting, single-phasing, and operating above base nameplate kilowatt or horsepower are not normal operating conditions.

open-transition transfer: A motor bus transfer (MBT) designed to trip the old source breaker before closing the new source breaker so that the two source breakers are open at the same time during the transfer process.

overload: Loading in excess of normal rating of equipment. For a motor, it is considered overloaded when operated above its base nameplate kilowatt or horsepower.

partial discharge: A localized electric discharge resulting from ionization in an insulation system when the voltage stress exceeds the critical value. This discharge partially bridges the insulation in the voids internal to the motor winding insulation.

residual voltage transfer: An open-transition method wherein the voltage magnitude at the motor bus falls below a predetermined level before the close command is issued to the new breaker. There is no supervision of the synchronous condition between the motor bus and the new source.

rotor: The rotating member of a machine.

NOTE—Most rotors have a current-carrying winding arranged in a fashion to generate a magnetic field. The current in the rotor winding may be induced from the stator or externally supplied, and may be either ac or dc. Certain rotors generate the magnetic field using permanently-magnetized regions; these typically do not have windings and thus do not carry current.

running thermal capability: A plot of maximum permissible time versus percent of rated current flowing in the motor winding when the motor is running.

sequential transfer: An open-transition method wherein closing of the new source breaker is supervised by an auxiliary contact of the old source breaker. Sequential transfer can be applied with the fast, in-phase, and residual methods of transfer to prevent closing the new source breaker should the old source breaker not open.

service factor: A multiplier that, when applied to the rated power, indicates a permissible power loading that may be carried under the conditions specified for the service factor.

simultaneous transfer: An open-transition method wherein there is no verification that the bus has been disconnected from the old source prior to closing the new source breaker. Simultaneous transfer can be applied with the fast, in-phase, and residual methods of transfer to prevent damage to equipment.

slow transfer: An open-transition method wherein a time interval, usually in excess of 20 cycles, occurs before the load is powered from another source. There is no supervision of the synchronous condition between the motor bus and the new source, or of the voltage magnitude of the motor bus.

spark: A sudden and irreversible transition from a stable corona discharge to a stable arc discharge. It is a luminous electrical discharge of short duration between two electrodes in an insulating medium. It is generally brighter and carries more current than corona, and its color is mainly determined by the type of insulating medium. It generates radio noise of wider frequency spectrum (extending into hundreds of megahertz) and wider magnitude range than corona. A spark is not classified as corona. Sparking can also include static discharge, sparking due to mechanical contact, and capacitive discharges (i.e., across bearing oil film and separating switch contacts).

starting current: The current required by the motor during the starting process to accelerate the motor and load to operating speed. Maximum starting current at rated voltage is drawn at the time of energizing.

starting time: The time required to accelerate the load to operating speed.

starting torque: The rated motor torque capability during start at rated voltage.

stator: The stationary component of an ac motor that contains the armature winding and stator core.

synchronous bus transfer or reclose: An open-transition motor bus transfer or reclose employing the fast transfer–supervised or in-phase transfer methods wherein the breaker close is supervised by taking into account the rapid movement and acceleration of phase angle between the decaying motor bus voltage and frequency and the new source voltage and frequency to determine that the breaker contacts are closed at or near zero phase coincidence.

thermal limit curve (cold): A plot of maximum permissible time versus percent of rated current flowing in the motor winding when the motor is started from ambient temperature.

thermal limit curve (hot): A plot of maximum permissible time versus percent of rated current flowing in the motor winding when the motor is started from rated operating temperature.

trip circuit monitor (TCM): A device/function that monitors an associated circuit breaker's trip circuit for continuity and for the presence of tripping voltage, and sets an externally readable alarm when continuity or tripping voltage is lost (a surrogate for the traditional red light on relay and control panels).

wound rotor winding: The rotor circuit on a wound rotor induction motor, which consists of a polyphase winding that carries the alternating current produced by induction.

zone of protection: Zones of protection are logical divisions of the power system used to isolated faulted sections, i.e., generators, transformers, buses, transmission lines, distribution lines or cable circuits, and motors. Zones are classified as primary and/or backup.

3.2 Acronyms and abbreviations

AFD	adjustable frequency drive (ASD is the IEEE-preferred term)
AHJ	authority having jurisdiction
AIT	autoignition temperature
ASD	adjustable speed drive
CEC	Canadian Electrical Code
CMV	common-mode voltage
CS	clear space (for time current characteristic curves)
CT	current transformer
DCS	distributed control system
DPFV	drip-proof forced ventilated
FLC	full load current
FLT	full load torque
GOOSE	generic object-oriented substation event

HDO	high-drop out
HFCT	high frequency current transformers
HRG	high resistance ground
HSCT	high sensitivity current transformer
HVCC	high-voltage coupling capacitor
IC	IC Code
I/O	input/output
IOC	instantaneous overcurrent
IP	IP Code
LCI	load commutated inverter
LFL	lower flammable limit
LRC	locked rotor current
LV	low-voltage
LVPCB	low-voltage power circuit breaker
MBT	motor bus transfer
MCC	motor control center
MCCB	molded-case circuit breaker
MESG	maximum experimental safe gap
MIC	minimum igniting current
MIE	minimum ignition energy
MOV	metal oxide varistor
MV	medium-voltage
NEC®	National Electrical Code[12]
NRTL	nationally recognized testing laboratory
NTC	negative temperature coefficient resistors
ODE	opposite drive end
ODP	open drip-proof
OEM	original equipment manufacturer
OLPD	online partial discharge
PD	partial discharge
pu	per unit
PTC	positive temperature coefficient resistors
PWM	pulse-width modulation
RP	recommended practice
RPM	revolutions per minute

[12]National Electrical Code, NEC, and NFPA 70 are registered trademarks of the National Fire Protection Association.

RTD	resistance temperature detector
SCR	silicon controlled rectifier
SF	service factor
SSC	stator slot couplers
T Code	Temperature Code or Identification Number per 2014 NEC Table 500.8(C)
TCM	Trip circuit monitor, alarm
TEAAC	totally enclosed air-to-air cooled
TEFC	totally enclosed fan-cooled
TEFV	totally enclosed force ventilated
TENV	totally enclosed nonventilated
TEPV	totally enclosed pipe-ventilated
TEWAC	totally enclosed water-to-air cooled
TFE	tetrafluoroethylene
TOC	time overcurrent
UFL	upper flammable limit
UPS	uninterruptible power supply
VFD	variable frequency drive (adjustable speed drive [ASD] is the IEEE-preferred term)
VSD	variable speed drive (adjustable speed drive [ASD] is the IEEE-preferred term)
VT	voltage transformer
WPI	weather protected type I
WPII	weather protected type II

4. General discussion

4.1 Introduction

This recommended practice applies specifically to ac single-phase and three-phase motors and dc motors. Many factors should be considered in choosing motor protection: motor importance, load importance and characteristics, motor rating (from one to several thousand horsepower), thermal limit of rotor or stator, environment, power system source and system grounding method, type of motor controller, etc. Protection for each specific motor installation should meet the requirements of the application. Power quality of the plant distribution system should be given appropriate attention, especially with regard to voltage sags and surges, harmonics, service interruptions, and operation of distribution line reclosers.

Items in Clause 5 and Clause 6 should be considered as checklists when deciding upon protection for a given motor installation. After the types of protection have been selected, manufacturers' bulletins should be studied to improve proper application of the specific protection chosen.

The selection of the motor protection schemes, starting method, etc. depend on the overall power system. The information contained in the IEEE Color Book® series and the new replacement IEEE 3000® series documents provide valuable information for the overall system design and protection. Refer to IEEE Std 3001.5™, IEEE Std 3001.8™, IEEE P3001.11 D8, IEEE Std 3003.2™, IEEE Std 3004.1™, IEEE Std 3004.5™, IEEE Std 3006.5™, IEEE Std 3006.7™, IEEE Std 3006.9™, IEEE Std 3007.1™, IEEE Std 3007.2™, and IEEE Std 3007.3™.

4.2 Low-voltage systems

Low-voltage (LV) systems are nominally 1000 V or less. NEMA MG-1-2011 lists the standard motor nameplate ratings along with the preferred size limits for several standard motor voltages. At present, a maximum of 575 V and 750 kW (1000 hp) exists for motor nameplate ratings. Table 1 below shows typical LV motor ratings for various 60 Hz system voltages.

NOTE—The nominal system voltage is generally rated higher to allow for voltage drop between the source and the terminal of the motor.

Table 1—Nameplate voltage ratings of standard LV induction motors

Nominal system voltage	Typical motor nameplate voltage
Single-phase system 120 V 240 V	Single-phase motor 115 V 230 V
Three-phase system 208 V 240 V 480 V 600 V	Three-phase motor 200 V 230 V 460 V 575 V

4.3 Medium-voltage systems

Medium-voltage (MV) systems range above 1000 V and up to 69 kV. Industrial and commercial power systems typically operate with distribution voltages of 2.4 kV, 4.16 kV, 6.9 kV, and 13.8 kV and above. The selection of the motor voltages is described in Clause 3.4 of IEEE Std 141™-1993 (*IEEE Red Book*™). Table 2 below shows typical MV motor ratings for various 60 Hz system voltages.

Table 2—Nameplate voltage ratings of standard MV induction motors

Nominal system voltage	Typical motor nameplate voltage
Three-phase system 2400 V 4160 V 6900 V 13.8 kV	Three-phase motor 2300 V 4000 V 6600 V 13.2 kV

5. Factors to consider in protection of motors

5.1 Motor characteristics

Motor characteristics include type (i.e., induction or synchronous), speed, voltage, power rating (kW or hp), service factor, NEMA design (i.e., A, B, C, or D, which are the torque and speed characteristics for LV and MV motors as described in NEMA MG 1-2011), application, power factor rating, type of motor enclosure, bearing lubrication types, arrangement of windings and their temperature limits, thermal capabilities of rotor and stator during starting, running, and stall conditions. See Table 3.

Table 3—Typical characteristics and applications of fixed frequency medium ac squirrel-cage induction motors (NEMA MG 10-2013 [B44])

Polyphase characteristics	Locked rotor torque (% rated load torque)	Pull-up torque (% rated load torque)	Breakdown torque (% rated load torque)	Locked rotor current (% rated load current)	Slip	Typical applications	Relative efficiency
Design A Normal locked rotor torque and high locked rotor current	70 to 275[a]	65 to 190[a]	175 to 300	Not defined	0.5% to 5%	Fans, blowers, centrifugal pumps and compressors, motor to generator sets, etc., where starting torque requirements are relatively low	Medium or high
Design B Normal locked rotor torque and normal locked rotor current	70 to 275[a]	65 to 190[a]	175 to 300[a]	600 to 800	0.5% to 5%	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low	Medium or high
Design C High locked rotor torque and normal locked rotor current	200 to 285[a]	140 to 195[a]	190 to 225[a]	600 to 800	1% to 5%	Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required	Medium
Design D High locked rotor torque and high slip	275	Not defined	275	600 to 800	≥ 5%	High peak loads with or without flywheels such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping, and wire-drawing machines	Medium

Table continues

Table 3—Typical characteristics and applications of fixed frequency medium ac squirrel-cage induction motors (NEMA MG 10-2013 [B44]) *(continued)*

Polyphase characteristics	Locked rotor torque (% rated load torque)	Pull-up torque (% rated load torque)	Breakdown torque (% rated load torque)	Locked rotor current (% rated load current)	Slip	Typical applications	Relative efficiency
IEC Design H High locked rotor torque and high locked rotor current	200 to 285[a]	140 to 195[a]	190 to 225[a]	800 to 1000	1% to 5%	Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required	Medium
IEC Design N Normal locked rotor torque and high locked rotor current	75 to 190[a]	60 to 140[a]	160 to 200[a]	800 to 1000	0.5% to 3%	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low	Medium or high
NOTE—These typical characteristics represent common usage of the motors—for further details consult the specific performance standards for the complete requirements.							

[a]Higher values are for motors having lower horsepower ratings.

Reprinted by permission of the National Electrical Manufacturers Association from NEMA MG10–2013, Table 1.

5.2 Motor-starting conditions

5.2.1 General

Motor-starting conditions include across-the-line (full voltage non-reversing or reversing) or reduced voltage, adjustable speed drive (ASD), voltage drop and degree of inrush current during starting, repetitive starts, and frequency and total number of starts. For the number and frequency of starts refer to NEMA MG-1-2011, Section 12.54 and NEMA MG-10-2013, Table 7 [B44]. See Figure 1 and Padden and Pillai [B48].

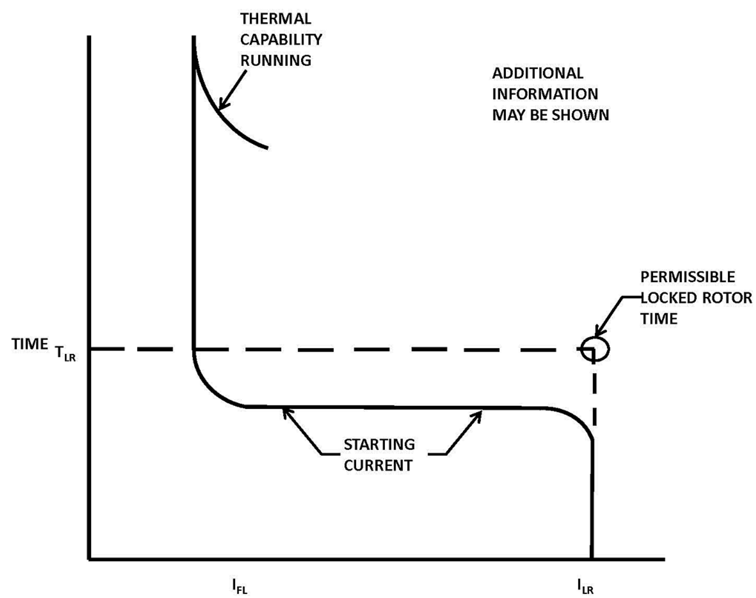


Figure 1—Typical motor-starting and capability curves (specific motor terminal voltage and for cold start)

Protection methods and settings are also affected by the starting methods. A comparison of electro-mechanical reduced-voltage starters is given in Table 4, similar to Table 10–17 in IEEE Std 141-1993 (*IEEE Red Book*™). Various starting methods are discussed in 5.2.2 through 5.2.8. In Clause 9 of IEEE Std 399™, motor starting studies are described in more detail. If for example in Table 4, normal inrush is 6 times full load current and an 80% tap autotransformer start is applied, the actual inrush multiplier used for determining the appropriate motor representation in the calculations is (6 × 0.67) × full load current = (4.02) × full load current. Resistor or reactor starting limits the line starting current by the same amount as motor terminal voltage is reduced (that is, 65% of applied bus voltage gives 65% of normal line starting current). Wye (Y) -start, delta (Δ) -run starting delivers 33% of normal starting line current with full voltage at the motor terminals. The starting current at any other voltage is, correspondingly, reduced by the same amount. Part winding starting allows 60% of normal starting line current at full voltage and reduces inrush according to other voltages. As shown in Table 4, the starting torque is also affected by the starting method.

Table 4—Comparison of electro-mechanical reduced-voltage starters

	Autotransformer[a]			Primary resistor or reactor		Part winding[b]	Wye start-delta run
	50% Tap	65% Tap	80% Tap	65% Tap	80% Tap	2-step	
Starting current drawn from line as percentage of that which would be drawn upon full-voltage starting[c]	28%	45%	67%	65%	80%	60%[c]	33$^{1}/_{3}$%
Starting torque developed as percentage of that which would be developed on full-voltage starting	25%	42%	64%	42%	64%	50%	33$^{1}/_{3}$%
	Increases slightly with speed			Increases greatly with speed			
Smoothness of acceleration	Second in order of smoothness			Smoothest of reduced-voltage types in Table 4. As motor gains speed, current decreases. Voltage drop across resistor decreases and motor terminal voltage increases.		Fourth in order of smoothness	Third in order of smoothness
Starting current and torque adjustment	Adjustable within limits of various taps			Adjustable within limits of various taps			Fixed

[a]Closed transition.
[b]Approximate values only. Exact values can be obtained from motor manufacturer.
[c]Full-voltage start usually draws between 500% and 600% of full load current.

5.2.2 Solid-state reduced-voltage motor start

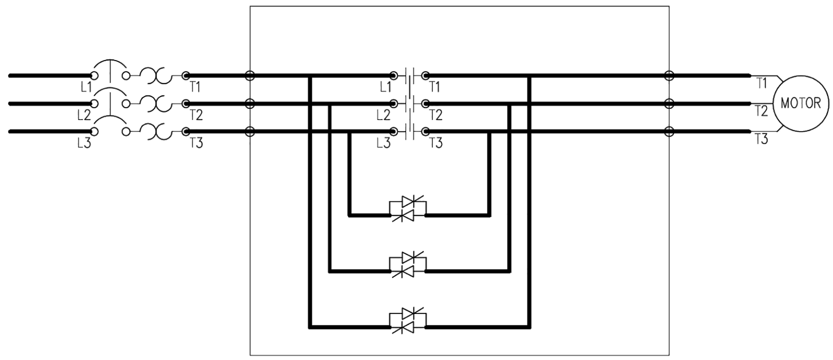
As discussed in more detail in 10.6.3.6 of IEEE Std 141-1993 (*IEEE Red Book*™), solid-state motor starters can control the starting cycle and provide reduced-voltage starting for standard ac squirrel-cage induction motors. They provide an adjustable, controlled acceleration and eliminate high power demands during starting. These starters are available in standard models for motors rated from fractional sizes to over 4500 kW (6000 hp). One type of reduced-voltage starter uses six thyristors in a full-wave configuration to vary the input voltage from zero to full on, so that the motor accelerates smoothly from zero to full running speed. The thyristors are activated by an electronic control section that has an initial step voltage adjustment. This adjustment, combined with a ramped voltage and current limit override, provides constant current (torque) to the motor until it reaches full speed. Figure 2 shows a typical solid-state reduced-voltage motor starter schematic with internal shorting device. Figure 3 shows a typical solid-state reduced-voltage motor starter schematic with external shorting device controlled by an "End of Start" relay. For short-circuit protection, refer to the manufacturer's recommendations and literature, and also to NEC® Article 430 and Section 430.52(C)(5).

Variations in the design of starting circuit are as follows:

a) The solid-state reduced-voltage motor starter maintains a constant level of kilovolt-amperes and reduces sudden torque surges to the motor. The current limiter, in conjunction with the acceleration ramp, holds the current constant at a preset level during the start-up period. When the start cycle is complete, the motor is running at almost full voltage with, essentially, a sine wave in each phase.

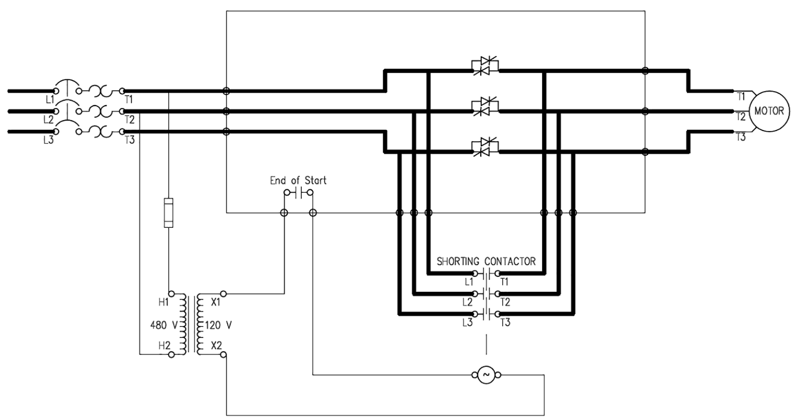
b) Thyristors are used only during the starting phase. At full voltage, a shorting contactor closes and the circuit operates as a conventional electromechanical starter.

c) A starter with linear-timed acceleration uses a closed-loop feedback system to maintain the motor acceleration at a constant rate. The required feedback signal is provided by a tachometer (ac, dc, or encoded) coupled to the motor.



Courtesy of Schneider Electric.

Figure 2—Typical solid-state reduced-voltage motor starter with internal shorting device, schematic



Courtesy of Schneider Electric.

Figure 3—Typical solid-state reduced-voltage motor starter with external shorting device controlled by "End of Start" relay, schematic

5.2.3 ASD start

ASDs can also be used as a soft-start with the added features of multiple starts per hour, adjustable acceleration and deceleration rates, and 100% or higher starting torque. Refer to 9.3.8 for a discussion on using ASDs to start and operate multiple motors.

An example of ASD starting is detailed in a PCIC paper presented by LeDoux, et al., "Starting Large Synchronous Motors in Weak Power Systems" [B35].

5.2.4 Autotransformer start

Subclause 10.6.3.3 of IEEE Std 141-1993 (*IEEE Red Book*™) discusses autotransformer start in more detail. Autotransformers are used for limiting starting current and torque on polyphase induction motors to comply with power supply regulations or to avoid excessive shock to the driven machine, or to limit excessive voltage

drop. Overload and undervoltage protection are provided. These are equipped with mechanical interlock to assure proper starting sequence. Taps are provided on the autotransformer for adjusting starting torque and current. Since the autotransformer controller reduces the voltage by transformation, the starting torque of the motor will vary almost directly as does the line current, even though the motor current is reduced directly with the voltage impressed on the motor.

Autotransformer magnetic systems are the same as the manual systems described above, but suitable for remote control. They have a timing relay for adjustment of time at which full voltage is applied.

To overcome the objection of the open-circuit transition associated with an autotransformer starter, a circuit known as the Korndorfer connection is in common use. This type of starter requires a two-pole and a three-pole start contactor. The two-pole contactor opens first on the transition from start to run, opening the connections to the neutral of the autotransformer. The windings of the transformer are then momentarily used as series reactors during the transfer, allowing a closed-circuit transition. Although it is somewhat more complicated, this type of starter is frequently used on high-inertia centrifugal compressors to obtain the advantages of low line-current surges and closed-circuit transition.

5.2.5 Primary resistor or reactor start

As discussed in 10.6.3.3 of IEEE Std 141-1993 (*IEEE Red Book*™), automatic reduced-voltage starter designed for geared or belted drive where sudden application of full-voltage torque must be avoided. Inrush current is limited by the value of the resistor or reactor; starting torque is a function of the square of the applied voltage. Therefore, if the initial voltage is reduced to 50%, the starting torque of the motor will be 25% of its full-voltage starting torque. A compromise must be made between the required starting torque and the inrush current allowed on the system. It provides both overload and undervoltage protection and is suitable for remote control. The resistor or reactor is shorted out as speed approaches rated rpm.

5.2.6 Part-winding start

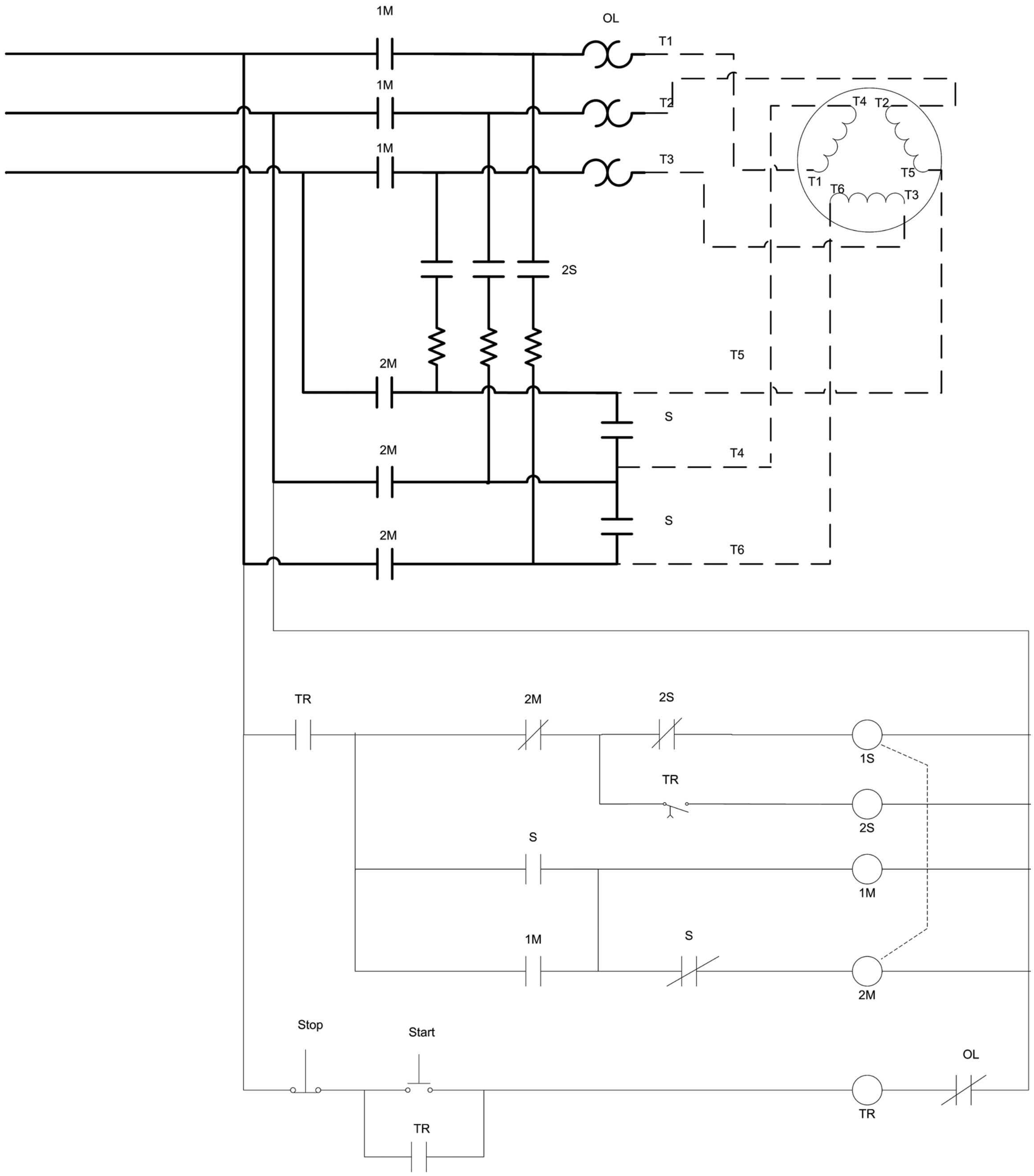
As discussed in more detail in 10.6.3.3 of IEEE Std 141-1993 (*IEEE Red Book*™), part-winding starters are used on light or low-inertia loads where the power system requires limitations on the increments of current inrush. The torque characteristics are discussed in more detail in section 14.38 of NEMA MG-1-2011. It consists of two magnetic starters, each selected for one of the two motor windings, and a time-delay relay controlling the time at which the second winding is energized. It provides overload and undervoltage protection and is suitable for remote control.

5.2.7 Wye-delta start

Subclause 10.6.3.3 of IEEE Std 141-1993 (*IEEE Red Book*™) discusses wye-delta, also known as star-delta, in more detail. This type starter is most applicable to starting motors that drive high-inertia loads with resulting long acceleration times, such as a centrifuge that takes 45 minutes to an hour to accelerate to full speed, while other loads accelerate in seconds. When the motor has accelerated on the wye (or star) connection, it is automatically reconnected by contactors for normal delta operation. This type of starter requires six motor leads.

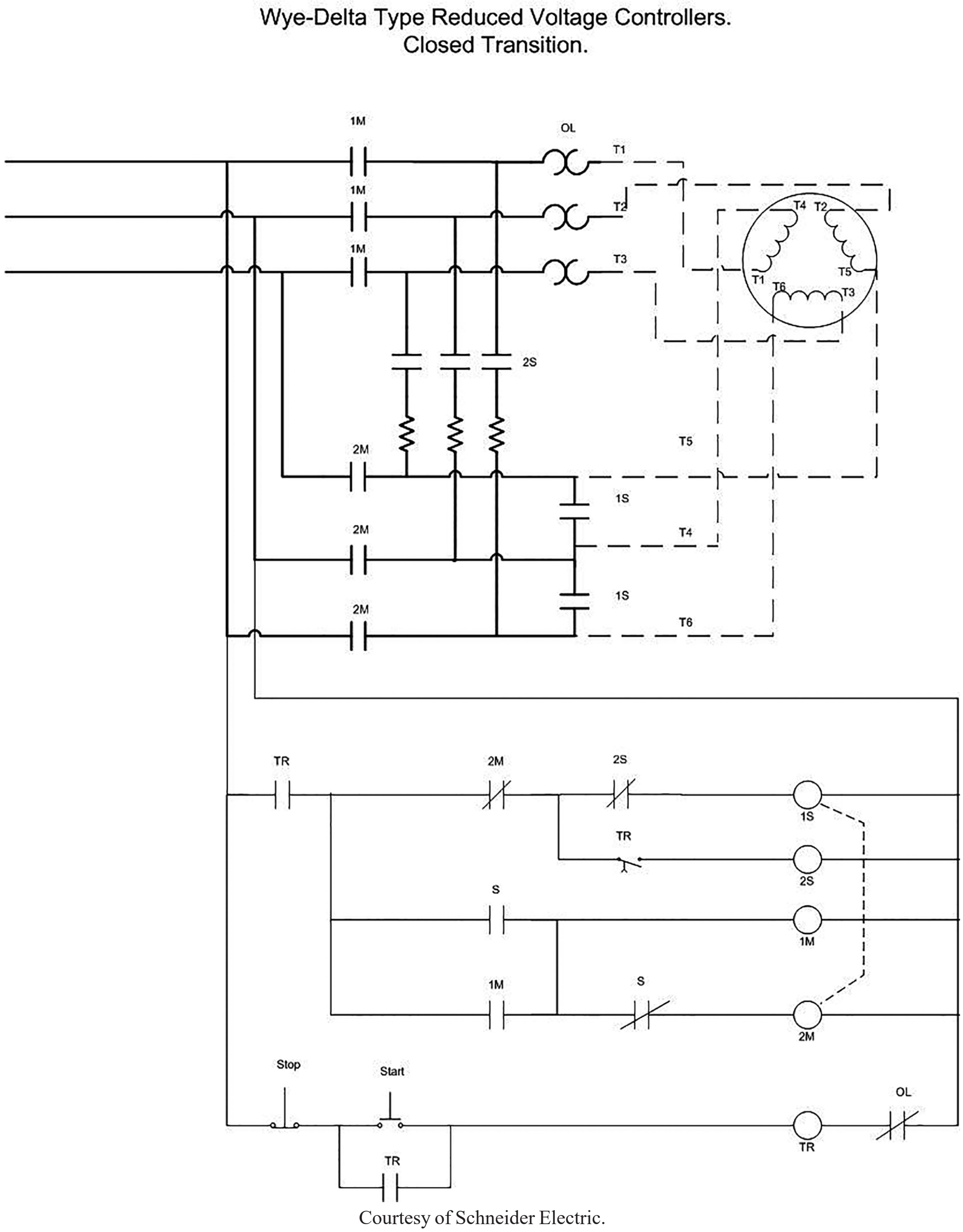
In selecting the type of reduced-voltage starter, consideration should be given to the motor control transition from starting to running. In a closed-circuit transition, power to the motor is not interrupted during the starting sequence as shown in Figure 5, whereas an open-circuit transition power to the motor is interrupted as shown in Figure 4. Closed-circuit transition, such as Figure 5, is recommended for all wye-delta starter applications to reduce inrush voltage disturbances and torque pulses.

Wye-Delta Type Reduced Voltage Controllers.
Closed Transition.



Courtesy of Schneider Electric.

Figure 4—Wye-delta reduced-voltage starter, open transition



Courtesy of Schneider Electric.

Figure 5—Wye-delta reduced-voltage starter, closed transition

5.2.8 Multi-speed motor start

Subclause 10.6.3.5 of IEEE Std 141-1993 (*IEEE Red Book*™) discusses this in more detail. Multi-speed motor controllers are designed for the automatic control of two-, three-, or four-speed squirrel-cage motors of

either the consequent-pole or separate-winding types. They are available for constant-horsepower, constant torque, or variable torque three-phase motors used on fans, blowers, refrigeration compressors, and similar machinery.

CAUTION

Caution should be taken when the motor is slowing down to not energize the slow speed winding while the motor is rotating above synchronous speed because it can cause high torque, voltage spikes, and current spikes.

5.3 Ambient conditions

Ambient conditions include maximum and minimum temperatures, altitude, adjacent heat sources, and ventilation arrangement. NEMA designed motor temperature rises are based upon a reference ambient temperature of 40 °C and a maximum altitude of 1000 m.

5.4 Driven equipment

Load characteristics are important in the selection and protection of the motor; otherwise, the driven equipment may lead to a locked rotor condition, failure to reach normal speed (stalling), excessive heating during acceleration, or overloading. See Figure 6, which illustrates the relationship between the accelerating current of a motor versus the thermal damage limits of the motor during accelerating and running conditions. Present practice is to add a solid-state reduced-voltage starter or an ASD for motors that may have accelerating problems or to add an ASD for motors that could be operated at a reduced speed for some period of the duty cycle. The protection of motors driven by ASDs is discussed in Clause 9. For a detailed study of reduced-voltage starting, refer to the subclauses of 5.2, Chapter 7 of IEEE Std 241™-1990, and IEEE P3001.11/D8.

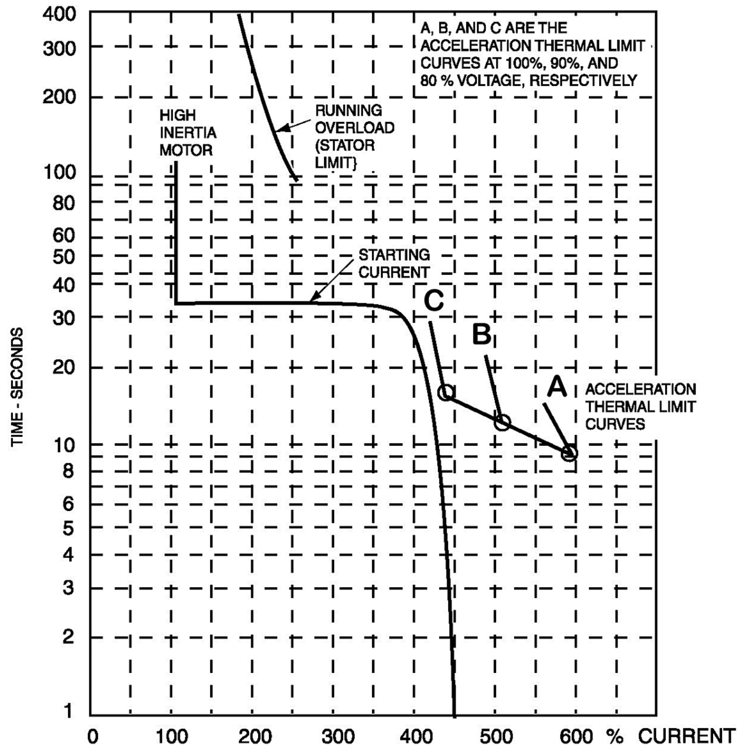


Figure 6—Typical time-current and thermal limit characteristic curves

5.5 Power system quality

Power system quality issues include types of system grounding, exposure to lightning and switching surges, capacitors and their controls for power-factor correction, fault capacity, exposure to automatic reclosing or transfer, possibilities of single-phase supply (e.g., broken conductor, open disconnect switch or circuit breaker pole, opened fuse), and other loads that can cause voltage unbalance. Another factor is harmonics, which may cause motor overheating and affect the performance of electronic protective devices; see IEEE Std 519™.

5.6 Motor importance

Factors that determine motor importance include motor cost, forced outage costs, amount of maintenance and operating supervision to be provided, and ease and cost of repair or replacement. For example, in processing facilities, large unspared pumps and compressors are typically of high importance because loss of the motor normally means the process unit can no longer operate; and due to their size, these motors take a long time to repair or replace. A motor that is important to a plant's operating continuity or process safety should include a pre-trip alarm for operator intervention as a first step. An example would be to initiate an alarm when the stator winding temperature has risen to a point above full load temperature rise and the rated temperature rise of the winding insulation. This alarm could mean the motor is being overloaded or there has been a failure of the cooling system such as dirty filters or loss of cooling water.

5.7 Load side faults for motor controllers

Although most of 5.7 concerns low-voltage applications, the principles apply to MV applications of motor controllers as well. Calculation of available fault current in a circuit is described in Chapter 2 of IEEE Std 242™-2001 (*IEEE Buff Book*™), and IEEE Std 399 (*IEEE Brown Book*™) [B27]. Fuse and circuit breaker pro-

tection for conductors in feeder and branch circuits are described in Chapter 5, Chapter 6, and Chapter 7 of IEEE Std 242-2001 (*IEEE Buff Book*™).

NOTE—Fuses and circuit breakers are rated for connection to available fault current sources on the basis of protecting the conductors on the load side of the circuit breaker or fuse.

In a motor controller, the above philosophy does not necessarily extend to protect the motor controller or its compartment. For proper protection of the motor controller, the fuse or circuit breaker (or motor circuit protector) that the controller manufacturer has had tested by a nationally recognized testing laboratory (NRTL) for the rated fault current available at its line terminals should be used. A motor circuit protector has an instantaneous only trip element, similar in construction to a molded-case circuit breaker (MCCB), and is described in 7.1.4 of IEEE Std 242-2001 (*IEEE Buff Book*™), IEEE Std 1015™-2006 (*IEEE Blue Book*™), and IEEE Std 3004.5.

Such motor controllers for best results should bear an NRTL listing for connection to available currents higher than the currents found in the power supply of the plant system under consideration or projected plant expansion fault duty. The NRTL-listed controller may still be substantially damaged by a load side fault downstream of the controller. If protection is necessary to reduce damage to the controller itself, the controller manufacturer should be consulted, or Type 2 protection should be specified in accordance with IEC 60947-4-1-2012 [B22]. Type 1 protection will reduce major damage but replacement of some motor control center components may be necessary after a fault occurs.

Controllers should be protected with fuses or circuit breakers where the combination controllers are rated for the available fault current. This subject is covered more thoroughly under protection of low-voltage motors in 7.1 of IEEE Std 242-2001 (*IEEE Buff Book*™), IEEE Std 1015-2006 (*IEEE Blue Book*™), and IEEE Std 3004.5.

5.8 Ground faults

The magnitude of ground fault currents depends on the type of system grounding employed. Assuming no other ground exists on the power system, the level of damage experienced in a motor from an internal ground fault increases as the system grounding utilized goes from a high resistance grounded system to a low resistance grounded system to a solidly grounded system. Low values of internal ground fault currents on high resistance or low resistance grounded systems will normally create damage to the windings, but not the core material of the machine as long as they are removed within normal clearing times. However, on solidly grounded systems, the high ground fault currents can quickly lead to severe damage to the windings and escalate to stator iron damage and even possibly damage to the rotor as well. Detection of these high level ground faults should lead to very fast clearing times of the ground fault. The cost and time to repair a machine increases as the level of the ground fault current increases and the time to clear the fault increases. As the level of damage increases, the potential for having to replace the machine increases as well because there comes a point where repair of the machine no longer makes economic sense as long as a replacement can be found. This subject is treated in more depth in Chapter 8 of IEEE Std 242-2001 (*IEEE Buff Book*™).

5.9 Maintenance capability and schedule

5.9.1 Introduction

Maintenance capability and schedule are important factors. Selection of complex protection that cannot or will not be appropriately maintained can lead to inadequate protection. Likewise, the selection and setting of overload protection does not prevent inadvertent setting changes due to normal vibration or ambient conditions, such as low-voltage controllers with non-ambient compensated bi-metallic overloads. Backup protection should be coordinated to operate if primary protection fails to operate. Maintenance is covered in Chapter 16 of IEEE Std 242-2001 (*IEEE Buff Book*™), IEEE 3007 series of standards particularly IEEE Std 3007.2, NFPA 70B [B45], and the manufacturer's recommendations. Refer to IEEE Std 1068™-2015 [B28] for repair

and rewinding of motors and ANSI/EASA AR100–2015 [B2] for repair of rotating electrical apparatus. Protective device settings should be verified prior to returning a motor to service that has been repaired.

Motors are rotating machinery and proper condition monitoring should be performed for reliable operation especially for critical motors.

5.9.2 Condition monitoring, online (trending)

Typical condition monitoring that can be done online is as follows:

— Vibration analysis (see 8.5.5)

— On-line partial discharge (OLPD) (see 8.5.4.6 and C.1) [B10], [B52], [B53], [B56], [B60], [B61], [B65], and [B66]

— Monitoring motor insulation online (see C.2)

5.9.3 Condition monitoring, periodic (trending)

Typical condition monitoring that can be done periodically off-line is as follows:

— Winding insulation resistance test, e.g., IEEE Std 112™ and IEEE Std 115™

— Polarization index, e.g., IEEE Std 43™

— Partial discharge (PD), e.g., ASTM D 1868, British Standards Institution [B9], and Stranges, Dunn, and Stone [B61]

— Power factor/tip up test for MV motors, e.g., IEEE Std 286™ [B25]

5.10 Service factor

The service factor (SF) of a motor is a multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading that may be carried under the conditions specified for the service factor. A service factor of 1.0 is the same as the nameplate rating. Refer to sections 1, 1.42, and 14.37 of NEMA MG 1-2011 for standard conditions.

5.11 Application considerations

For motors applied in general applications, the authority having jurisdiction (AHJ) may have general requirements for motor protection, such as low-voltage motors (reference NEC Article 430 III, IV, and V), motors over 1000 V (reference NEC Article 430 XI), and motors applied on ASD systems (reference NEC Article 430 X).

For motors applied in certain applications, the local codes and standards may have specific protection requirements such as continuity of power or selective coordination. The following list is a sample of applications and is not all-inclusive: elevators, dumbwaiters, escalators, moving walks, platform lifts, and stairway chairlifts (reference NEC Article 620); emergency systems (reference NEC Article 700); legally required standby systems (reference NEC Article 701); and fire pumps (reference NEC Article 695).

5.12 Motor and conductor protection

While the focus of this document is motor protection, it should be acknowledged by the designers and protection engineers that the motor protection devices also protect the motor circuit conductors. The motor circuit conductor protection should be included in the time-current coordination plots. The conductor protection

should comply with applicable codes and standards for the AHJ. The conductor size should be selected to provide adequate voltage during starting and running and adequate ampacity during running (see NEC Article 430 II and XI). In addition, during short-circuit the conductor insulation should maintain its integrity and be protected. For example, consider selecting higher temperature-rated insulation system such as thermoset with a short-circuit current temperature rating of 250 °C versus thermoplastic with some conductors with a short-circuit current temperature rating of 150 °C (Padden and Pillai [B48]).

When using the conductor damage curves the designer should know 1) the type of insulation, 2) the maximum continuous temperature rating of the insulation, and 3) the maximum short-circuit current temperature rating of the insulation. Table 5 below provides some examples of conductor types and temperature ratings. For Table 5, also refer to 2014 NEC Section 310.104. Data should be gathered from the manufacturer for the specific conductor used. Conductor damage curve data are available from some coordination software programs as well, but the engineer should know the insulation properties.

Table 5—Examples of 600 V conductor insulation types and their maximum short-circuit temperature[a]

Type of insulation NEC designation, trade name	Type letter	Continuous temperature rating (°C): Dry	Continuous temperature rating (°C): Wet	Short-circuit current temperature rating (°C)
Thermoset				
Cross-linked polyethylene Thermoset Moisture-resistant thermoset	RHH XHH RHW RHW-2 XHHW XHHW-2	90 dry 90 dry 75 dry 90 dry 90 dry 90 dry	90 damp 90 damp 75 wet 90 wet 90 damp/75 wet 90 wet	250
Cross-linked polyvinyl chloride Moisture-resistant thermoset	XHHW	90 dry	90 damp/75 wet	250
Chlorinated polyethylene Thermoset Moisture-resistant thermoset	RHH RHW-2	90 dry 90 dry	90 damp 90 wet	250
Ethylene propylene rubber Thermoset Moisture-resistant thermoset	XHH RHH XHHW-2 RHW-2	90 dry 90 dry 90 dry 90 dry	90 damp 90 damp 90 wet 90 wet	250
Styrene butadiene rubber Moisture-resistant thermoset	RHW	75 dry	75 wet	200
Butyl rubber Thermoset Moisture-resistant thermoset	RHH RHW RHW-2	90 dry 75 dry 90 dry	90 damp 75 wet 90 wet	200
Silicone rubber Silicone	SA SA (special)	90 dry 200 dry	90 damp 200 damp	250
Thermoplastic				
Polyvinyl chloride Heat-resistant thermoplastic Moisture and heat-re- sistant thermoplastic	THHN THHW THW THW-2 THWN THWN-2	90 dry 90 dry 75 dry 90 dry 75 dry 90 dry	90 damp 75 wet 75 wet 90 wet 75 wet 90 wet	150

[a]Consult the conductor manufacturer for specific conductor properties. Temperature ratings may also vary with the year of manufacture.

Courtesy of Padden Engineering, LLC.

The conductor damage curve is plotted on the coordination plot. The damage curve should be above and to the right of the motor overload and short-circuit protective device curves with clear space (CS) between the curves. Also refer to IEEE Std 242-2001 (*IEEE Buff Book*™).

5.13 Fixed capacitor applications

Fixed power factor correction capacitor applications should consider the following:

— Dependent upon the capacitor location, motor overload set point should be adjusted. Refer to 7.2.2 and Figure 15 for examples.

— Fixed capacitor will extend motor open circuit time constant and will increase the minimum time for blocking the motor starting to allow for motor residual voltage to reach an acceptable level. Contact the motor manufacturer for the motor equivalent circuit data with and without the fixed capacitor. Refer to Annex E for sample equations and calculations.

— Many process plants tend to implement motor re-acceleration scheme. Therefore, motor capacitor application may not be recommended for re-acceleration motors in the process plants unless there will be sufficient time to decay motor residual voltages as shown in Annex E. This should be discussed with plant process engineers.

6. Types of protection

6.1 Purpose of motor protection

6.1.1 Introduction

In a power system, the basic premise is that the delivered power is of acceptable quality to satisfy the needs of the facility. However, an abnormal condition can exist because of plant or site conditions or the external power supply. Depending upon the plant size, location, and on-site generation, conditions such as voltage transients, surges and sags, overfrequency and underfrequency, harmonics, and discontinuity may develop that require corrective action. For large facilities, the incoming power is likely monitored, and methods have probably been taken to protect the facility from abnormal conditions. These methods are important, because this recommended practice focuses upon only motor protection. For smaller installations or unusual locations, plant or site protection may be more integrated with motor protection.

The motor protective devices permit the motor to start and run, and initiate tripping and removal of the motor circuit from the power system when the motor stalls, does not accelerate, draws excessive current, overheats, vibrates excessively, and/or shows other symptoms of improper motor conditions. Detection of improper conditions are through measurement of voltage, current, temperature, frequency, harmonics, vibration, and speed, where appropriate. However, for the majority of small motors (i.e., less than 220 kW [300 hp]), overcurrent is the most prevalent means of detection.

In the discussion of protective devices in this recommended practice, reference is made to device numbers, which are described in IEEE Std C37.2™ and Annex B herein. In general, MV protection uses device numbers (or function numbers) especially because most of those schemes are much more complex than LV schemes, in lieu of using repetitive descriptions.

6.1.2 Typical protection functions

Typically, selecting motor protection is based on the motor output rating (hp or kW) and the voltage level (low or medium voltage). Refer to Table 6 for typical motor protection functions for commercial and industrial applications and refer to Annex B for descriptions of the functions. In Figure 7 and Figure 8, the one-line and three-line diagrams respectively are provided for the typical fused E2 contactor controlled protection

functions for a MV induction motor application using a fused disconnect for short-circuit protection, a vacuum contactor for control, and a multifunction motor protection relay (Device 11M) for overload protection. The multifunction motor protection relay can open the contactor for various conditions except short-circuit protection which is provided by the fuses. The 51N residually connected ground fault protection or the 50G zero sequence current transformer (CT) ground fault protection can be used in a MV low resistance grounded power system where the ground fault current does not exceed the break rating for the vacuum contactor in this example. For high resistance grounded power systems, ground fault elements typically alarm; however, for each individual motor, most industrial owners choose to trip the end device (e.g., motor) that has a ground fault, even if they are maintaining the system during the fault.

Table 6—Typical motor protection functions[1]

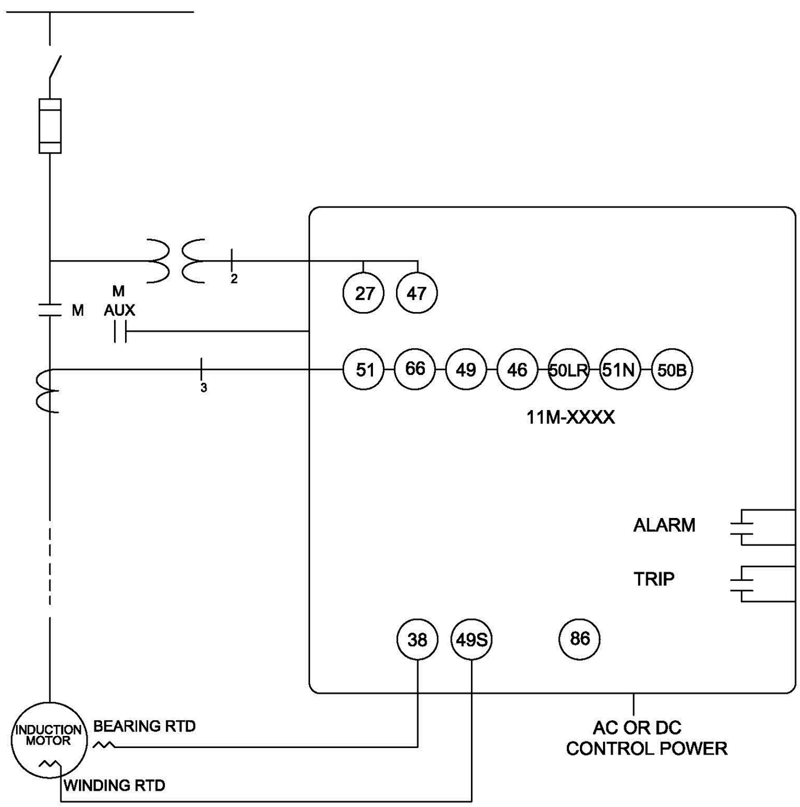
Description	Induction motors protection functions			Synchronous motors protection functions
	Minimum	Fused E2 contactor controlled	Critical service breaker controlled	Critical service breaker controlled
Distance relay				21 (or 51V)
Volts (U/O)	27	27	27/59	27/59
Directional power				32
Undercurrent			37	37
Bearing temperature protection		38	38	38
Vibration protection			39	39
Loss of field				40
Current balance		46	46	46
Negative sequence		47	47	47
Incomplete sequence				48
Thermal overload relay Overload operated by motor current (replica)	49	49	49	49
Stator winding thermal overload (also embedded detectors)	49S	49S	49S	49S
Breaker failure (breaker only)			50BF	50BF
IOC ground (zero sequence CT) (delayed on start) — Breaker trip or — Vacuum contactor within rating	50G	50G	50G	50G
TOC ground (residually connected) — Breaker trip or — Vacuum contactor within rating	51N	51N	51N	51N
IOC-locked rotor (delayed on start)		50LR	50LR	
TOC (V-voltage restrained)	51		51	51V (or 21)
Short-circuit	Fuse or Breaker, 50	Fuse	50	50
Current inhibit (blocks contactor opening)[2]	50B	50B		
Excitation check relay				53
Power factor				55
Field application relay				56
Voltage balance (loss of phase)			60	60
Number of starts	66	66	66	66
Directional overcurrent				67

Table continues

Table 6—Typical motor protection functions[1] *(continued)*

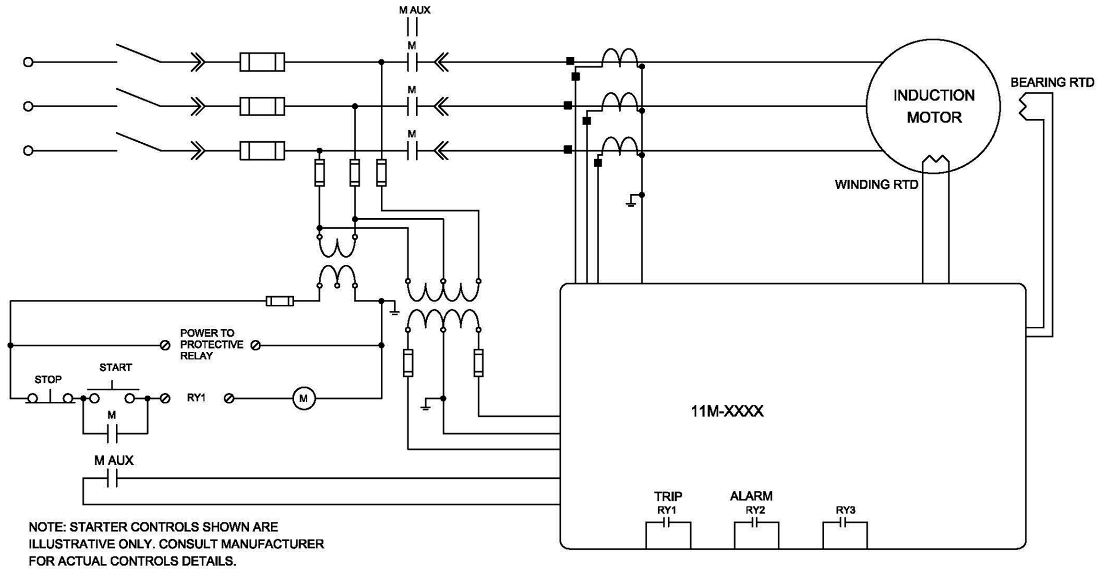
Description	Induction motors protection functions			Synchronous motors protection functions
	Minimum	Fused E2 contactor controlled	Critical service breaker controlled	Critical service breaker controlled
Trip circuit monitor, alarm			TCM	TCM
Out-of-step				78
Frequency			81U/O	81R, 81U/O
Lockout		86	86	86
Motor differential			87M	87M

[1]See also Table B.3, Security, communication, and other protection functions.
[2]*Current inhibit:* instantaneous phase overcurrent (50B) function blocks opening of the motor contactor when the fault current exceeds the interrupting rating of the contactor.



Courtesy of C&I Engineering.

Figure 7—MV induction motor 1-line diagram, typical minimum protection functions with fuses



Courtesy of C&I Engineering.

Figure 8—MV induction motor 3-line diagram, typical minimum protection functions with fuses

6.1.3 Protection relay testing

Protective relays should have provisions for testing and calibrating the relays using external power supplies without disconnecting the permanent wiring (e.g., test switches that are used for secondary injection testing and calibration). The AHJ, site experience, and manufacturer's recommendations provide information on the testing interval for electromechanical and solid-state relays.

For critical applications or for personnel considerations, each relay (e.g., 11M device) should have CT, voltage transformer (VT), and relay digital inputs and outputs wired to a relay test switch to allow for testing the relay with the motor circuit switching device in service. Testing provisions should include shorting of CT circuits and consideration for selectively disconnecting the relay from the trip circuits, as well as CTs, VTs, auxiliary power, and other circuits controlled by the relay. After a microprocessor type relay is commissioned and in service, some have self-diagnostics or self-testing to alarm if the relay malfunctions.

6.2 Abnormal power supply conditions

6.2.1 Introduction

Although overvoltage conditions have some consideration, that phenomenon draws less attention than undervoltage because of protection by surge arresters for momentary conditions and by relays for the less-common sustained overvoltage. Undervoltage conditions for LV and MV systems are discussed in this section. Further discussions concerning large motors can be found in 8.10.

6.2.2 Undervoltage (Device 27)

Undervoltage protection is used as follows:

a) *To prevent a motor from automatically restarting when voltage returns following an interruption*, as might happen with single-service arrangements or automatic transfer operations. Consideration should also be given as to the importance of the motor and whether conditions warrant that the motor

ride through voltage sags or drop out at some specific voltage, not to be energized until other conditions may have been met.

b) *To avoid excessive inrush to the total motor load* on the power system following a voltage sag or when voltage returns following an interruption.

c) *To avoid reaccelerating a motor before the field collapses*. Fast reclosing with the source voltage significantly out-of-phase with the motor bus voltage has been damaging and can occur if cooperation is lacking between the industrial plant and its power supplier. Consult the power supplier to learn their automatic reclosure timing and set the undervoltage relay timing accordingly. This delay is not a panacea, and some other forms of protection might be required, such as underfrequency relaying (Device 81).

For undervoltage use with bus transfer or reclosing, refer to 6.11.

6.2.3 Device 27, instantaneous or time delay

Undervoltage protection is either instantaneous (i.e., no intentional delay) or time-delay. Time-delay undervoltage protection should be used with motors important to continuity of service, providing it is satisfactory in all respects, to avoid unnecessary tripping on voltage sags that accompany external short-circuits. Examples follow of non-latching starters where time-delay undervoltage protection is not satisfactory and instantaneous undervoltage should be used:

NOTE—The limitations in item a) and item b) below could be overcome by using either a separate ac power source for control or battery control on the contactor to prevent its instantaneous dropout. In other words, the time-delay undervoltage feature can be applied directly to the main contactor. In addition, for synchronous machines, a voltage sag can result in a drop of field voltage when the field voltage is derived from the control power transformer for the magnetically held starter. This voltage drop can result in a reduction in field voltage to the point where there is a trip of the synchronous motor on field protection even before the contactor drops out. This situation can be avoided by deriving the field voltage from a reliable power supply not depended on steady control power transformer, such as from the output of a small uninterruptible power supply (UPS) included in the synchronous controller.

a) *Fusible switch or circuit breaker combination motor starters having ac magnetically held contactors used on systems of low three-phase fault capacity.* With the time-delay undervoltage scheme (without "off" time-delay), the contactor could drop out because of the low voltage accompanying a fault on the load side of the contactor before the supply fuse or circuit breaker opens to remove the fault. Unless provided with blocking for automatic restart, the contactor could then reclose into the fault. This problem does not exist if the available fault capacity is high enough to open the external fuse or circuit breaker before the contactor interrupts the fault current.

b) *Synchronous motors used with starters having ac magnetically held contactors.* With the time-delay undervoltage scheme (without "off" time-delay), the contactor could drop out on an externally caused system voltage sag, then reclose, and reapply the system voltage to an out-of-phase internal voltage in the motor. The high initial inrush could damage the motor winding, shaft, driven equipment, or foundation. For synchronous motors, an underfrequency relay might be required to avoid an out-of-step trip on reclose.

c) *Induction motors used with starters having ac magnetically held contactors.* The high inrush problem described in b) could also occur for large, two-pole squirrel-cage induction motors. If significantly out-of-phase reclosing represents a risk to the motor, then undervoltage protection alone might not suffice and underfrequency relay might be required. Reclosing may not be a problem with the 150 kW (200 hp) and smaller induction motors with magnetically held contactor starters because the internal voltages of these motors decay quite rapidly.

d) *Motors used on systems having fast automatic transfer or reclosing where the motor must be tripped to protect it before the transfer or reclosure takes place.* See b) and c) above regarding needing underfrequency relays also.

e) *When the total motor load having time-delay undervoltage protection results in excessive inrush current and voltage drop after an interruption, a problem could arise of not having sufficient system capacity to restart the motors.* Options include designing for a larger power capacity than needed for normal operations, removing some of the motor loads from automatic restarting, and grouping the auto-restarting motors into several smaller time-sequenced groups, each of which can successfully auto-restart as a group. Less-important motors should use instantaneous undervoltage protection. Time-delay undervoltage protection with varying time delays could be used on the motors with inrush that the system can handle. Sequencers are available for selecting the order of motor restarts, thus reducing the need for oversized transformers or lower transformer impedances. Caution should be observed when placing numerous controls within one device where common-mode failure could negate the benefits. A more thorough discussion can be found in 6.11.

6.2.4 Device 27, with latching contactor or circuit breaker

Motor switching devices, such as latching contactors or circuit breakers, inherently remain closed during periods of low or zero ac voltage. The following methods are used to trip open the devices:

a) Energize shunt trip coil from a battery.

b) Energize shunt trip coil from a separate, reliable source of ac. This ac source should be electrically isolated from the motor ac source to enhance reliability.

c) Energize shunt trip coil from a capacitor charged through a rectifier from the ac system. This method is commonly referred to as capacitor trip.

d) De-energize a solenoid and allow an undervoltage release to trip the contactor or circuit breaker. Refer to 7.5.3.

Item a) through c) are usually used in conjunction with voltage-sensing relays (see 6.2.7). For item d), it could have the solenoid operating directly, either on the ac system voltage or from a battery, where a relay would sense loss of ac voltage and de-energize the solenoid. The solenoid could be either instantaneous or time-delay.

6.2.5 Device 27, with ac magnetically held main contactor

Because the ac magnetically held main contactor (which supplies the motor) drops out on a loss of ac power, it provides an instantaneous undervoltage function. If automatic restart is required because of the process, two common approaches achieve time-delay undervoltage protection:

a) Permit the main contactor to drop out instantaneously, but provide a timing scheme (that starts timing when ac voltage is low or zero) to reclose the main contactor when normal ac voltage returns within some preset timing interval. Some of the timing schemes in use are as follows:

   1) Capacitor charged through a rectifier from the ac system. The charge keeps an instantaneous dropout auxiliary relay energized for an adjustable interval, which is commonly 2 s to 4 s.

   2) Standard timer that times when de-energized (e.g., pneumatic or inverse time-undervoltage relay).

b) Use a two-wire control. This control uses a maintained closed start button or operates from an external contact responsive to some condition such as process pressure, temperature, or level. The main contactor drops out with loss of ac, and recloses when ac voltage returns.

Neither arrangement provides perfect undervoltage protection and should not be used if automatic restarting could endanger personnel or equipment. Refer to 6.11 and Annex E.

6.2.6 Device 27, with separate control power for main contactor

Separate control power for the main contactor may be a dc magnetically held contactor sourced from a reliable battery system or ac power supplied from a separate source (i.e., UPS). With a separate control power source, the main motor contactor remains closed during low or zero ac voltage to the motor. Time-delay undervoltage protection is achieved using voltage-sensing relays (see 6.2.7). For this scheme, the separate control voltage should be monitored as well.

6.2.7 Device 27, with voltage-sensing relays

A commonly used type of voltage-sensing relay is the single-phase inverse time-undervoltage relay. There are also definite time undervoltage relays. Because an opened control fuse could cause tripping, two or three such time-undervoltage relays are sometimes used, connected to different phases, and wired so that all Device 27 relays must operate before tripping occurs or re-energization can be permitted.

Three-phase undervoltage relays are available. Many operate in response to the area of the voltage triangle formed by the phasors of the three-phase voltages. Alternatively, a voltage-balance relay (Device 60) could be used for opened fuse protection.

Although many older starters with individual protection relays exist in older facilities, the voltage sensing relay functions today are normally included in multifunction motor protection relays (Device 11M). These multifunction relays can provide single-phase inverse time undervoltage functions as well as definite time protection. Some of these multifunction relays also offer logic that detects one, two, or three open VT fuses. Some of these multifunction relays operate in response to the area of the voltage triangle formed by the phasors of the three-phase voltages.

When applying undervoltage protection with time delay, the time-delay setting should be chosen so that time-delay undervoltage tripping does not occur before all external fault-detecting relays have had an opportunity to clear faults from the system. This practice recognizes that the most frequent causes of low voltage are system faults; and when these faults are cleared, most induction motors can continue normal operation. For inverse time-undervoltage relays, their trip time versus system short-circuit current should be plotted to verify that these trip only after the system overcurrent protective relays. This procedure should be done for the most critical coordination condition, which exists when the system short-circuit capacity is minimum. This study should be included with normal systems studies concerning voltage drop, short-circuits, etc. Typical time delay at zero voltage is 2 s to 5 s.

For motors extremely important to continuity of service, such as some auxiliaries in electric generating plants, the undervoltage relay functions are used only to alarm. The motors providing fire pump service should be protected in accordance with applicable standards such as NFPA 20-2013 and NFPA 70-2014.

6.3 Phase unbalance protection (Device 46, current) (Device 47, voltage) (Device 60)

6.3.1 Devices 46, 47, and 60; relays

Several types of relays are available to provide phase unbalance protection, including single phasing. Most of these relays are described in Chapter 4 of IEEE Std 242-2001 (*IEEE Buff Book*™) and in IEEE Std C37.96™-2012. Further information about specific relays should be obtained from the various manufacturers. Most of the commonly used relays or functions in Device 11M are classified below. The user should select the protection functions necessary for the application and disable unused functions.

a) Phase current unbalance (Device 46). A device in a polyphase circuit that operates when polyphase currents are unbalanced. Mechanical phase current unbalance relays are induction disk devices that detect unbalance in the currents in the three phases. As such these devices have an inherent time delay. Occasionally, a timer is used to obtain additional delay. Because this relay cannot protect for unbalances less than 25%, its selection is questionable except for complete loss of one phase. Unfortunately, this device shares the same device number as the negative sequence overcurrent relay (Device 46) in item d).

b) Phase current unbalance high resistance ground (HRG) (Device 46). If users set current unbalance relay to trip in an HRG system and a ground fault occurs on the system, the Device 46 may initiate an undesired trip. Some protection relays for LV applications have a blocking function to avoid this situation. However, if the Device 46 relay does not block this situation, alarm only should be considered.

c) Reverse-phase (Device 46). A device in a polyphase circuit that operates when the polyphase currents are of reverse phase sequence.

d) Negative sequence overcurrent (Device 46). A negative sequence overcurrent relay is a time overcurrent relay with extremely inverse characteristics that operates at very small levels of negative sequence current. Settings are available to alarm before trip and to trip upon a limit of I_2^2t.

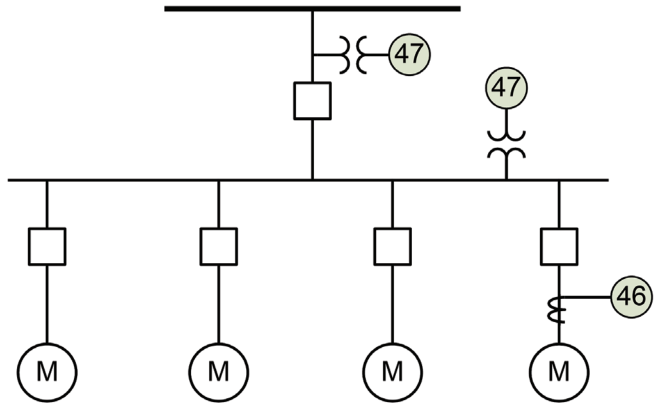
e) Negative sequence voltage (Device 47). Because negative sequence voltage relays operate instantaneously on negative sequence overvoltage, some external time delay might be necessary.

f) Voltage balance (Device 60). The voltage balance (60) element compares voltage sources to determine if there is a difference in voltage, i.e., for VTs determining if both input sources are present or if there is an open fuse losing one source. If a source is not present, then the output of this element blocks (removes permission) from tripping or starting elements. The voltage balance 60 relay is an older method than voltage-unbalance 47 protection, which is based on sequence components.

6.3.2 Devices 46, 47, and 60; purpose

The purpose of phase unbalance protection is to prevent motor overheating damage. Motor overheating occurs when the phase voltages are unbalanced. A small voltage unbalance produces a large negative sequence current flow in both synchronous and induction motors. The per-unit negative sequence impedance of either motor is approximately equal to the reciprocal of the rated voltage per-unit locked rotor current. When, for example, a motor has a locked rotor current equal to six times rated current, the motor has a negative sequence impedance of approximately 0.167 per unit (16.7%) on the motor rated input kilovoltampere base. When voltages having a 0.05 per-unit negative sequence component are applied to the motor, negative sequence currents of 0.30 per unit flow in the windings. Thus, a 5% voltage unbalance produces a stator negative sequence current equal to 30% of full load current. This situation can lead to a 40% to 50% increase in temperature rise.

Current unbalance (46) is measured in the motor feeder and has the advantage of being applied at each motor. It is easy to implement in multifunction motor protection relays, Device 11M. Measuring algorithms include the true negative sequence measurement and the difference between the maximum and minimum phase currents. For a negative sequence type element, the I_2 percent setting (20% to 25% of nameplate rated current) is approximately 4 to 5 times the percent voltage unbalance for the worst case nominal load condition. Refer to Figure 9 for optional VT locations for Device 47 and CT location for Device 46.

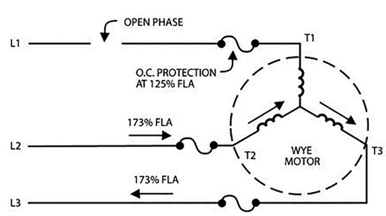


Courtesy of Basler Electric Company.

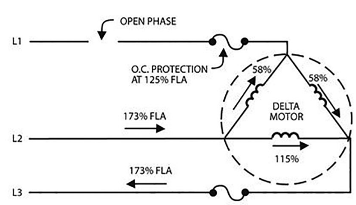
Figure 9—Device 47 VT locations and Device 46 CT location for motor protection

6.3.3 Devices 46, 47, and 60; single phasing

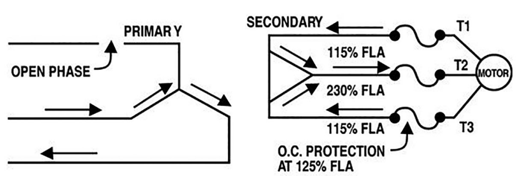
The extreme form of unbalance is the complete loss of voltage in one phase. Under these conditions, a three-phase motor is unable to start. If the single phasing occurs during full load running conditions, the current in the two energized phases increases above full load current for a wye connected motor (see Figure 10a). If the motor is delta connected, the current in the motor phase coils that are connected to the energized phases will see greater than full load amps and the two phase coils that are bisected by the lost phase will see less than full load current (see Figure 10b). These figures are applicable if the transformer is wye-wye connected. If the transformer is wye-delta connected, the same problem exists only the current values are different as shown in Figure 10c). In each case, adequate phase overcurrent protection is required.



a) Wye-wye connected transformer with wye connected motor



b) Wye-wye connected transformer with delta connected motor



c) Wye-delta connected transformer with wye or delta connected motor

Courtesy of EASA.

Figure 10—Loss-of-phase currents for various transformer and motor winding configurations

Many motors, especially in the higher horsepower ratings, can be seriously damaged by negative sequence current heating, even though the stator currents are low enough to go undetected by overload (overcurrent)

protection. (The standard service factor for large motors is 1.00.) Therefore, phase unbalance protection is desirable for all motors where the cost can be justified relative to the cost and criticality of the motor. Phase unbalance protection should be provided in all applications where single phasing is a strong possibility because of factors such as the presence of fuses, overhead distribution lines subject to conductor breakage, or disconnect switches (that might not close properly on all three phases). For large facilities, a bus phase-balance (negative sequence) overvoltage relay (Device 47) could be installed to alarm in a sensitive manner. This alarm would be set in conjunction with each large motor (phase balance) negative sequence overcurrent relays (Device 46). For small installations, a single phase balance (negative sequence) overcurrent relay might suffice for a large, critical motor; or alternatively one phase balance (negative sequence) bus overvoltage relay could be set to protect several motors, by alarming and/or tripping.

A general recommendation is to apply phase unbalance protection to all motors 750 kW (1000 hp) and above. For motors below 750 kW (1000 hp), the specific requirements should be investigated. Phase unbalance protection should also be considered for certain critical motors such as hermetic refrigeration chiller motors, air compressors, and similar motors.

6.3.4 Devices 46, 47, and 60; instantaneous or time-delay

Unbalanced voltages accompany unbalanced system faults. Therefore, phase unbalance protection should include sufficient delay to permit the system overcurrent protection to clear external faults without unnecessary tripping of the motor or motors.

Delay is also necessary to avoid the possibility of tripping on motor starting inrush. Therefore, unbalance protection having an inherent delay should be chosen. Another (high-risk) scheme is to use an auxiliary timer (Device 62). Its selection is important because the timer probably has a higher failure rate than the protective relay. If a time delay of more than 2 s or 3 s is used, the motor designer should be consulted.

6.4 Overcurrent protection (Device 51, inverse time) (Device 50, instantaneous)

Overcurrent sensing is the most frequently used method to monitor and protect the many power circuits in a facility. If a short-circuit occurs, action should be initiated without delay, whereas an overload within the service factor rating of the motor might not require any action. Under IEEE Std 242-2001 (*IEEE Buff Book*™) Chapter 15 guidelines, no delay should occur in the operation of the protection for circuit components (e.g., motors) upon sensing a fault, with backup protection coordinated by being delayed in time or overcurrent magnitude, or both.

Motor branch circuit protection is to operate whenever a motor fails to accelerate to designed operating speed, when the motor-running current exceeds normal limits, and when a short-circuit is detected. Normally, time overcurrent devices are used to protect against overloads and the failure to accelerate, whereas instantaneous devices operate without any intentional delay for short-circuit protection. For cyclic loads, the Device 49 thermal model discussed in 8.2 should be considered for motor thermal overload protection (Ransom and Hamilton [B51]).

Depending upon the motor rating and voltage, the devices for performing these functions are of different construction. For MV or large motors, the protection can be three phase–overcurrent protective relays or one multifunction motor protection relay (Device 11M), which would include such other protective functions as accelerating characteristics, current unbalance, differential overcurrent, ground fault current, and loss of load. Normally, such complex protection would not be provided for unimportant or inexpensive low-voltage motors, although capable multifunction relays are available for low-voltage motor protection. In addition, some motors might be supplied directly from low-voltage switchgear and use the protective characteristics described in IEEE Std C37.17™ and shown in Chapter 7 of IEEE Std 242-2001 (*IEEE Buff Book*™). The decision on whether to use low-voltage switchgear is usually influenced by the frequency of motor starts because motor controllers are rated for a considerably greater number of operations; and LV switchgear has higher ampacity and interrupt ratings.

6.5 Ground fault relay

This is a classic relay for ground fault detection. It is typically used for MV motors, large motors greater than 750 kW (1000 hp), or motors with a neutral. Various methods of ground protection are available such as ground sensing, zero sequence current sensing and residual current sensing. Refer to the discussion on 50G for zero sequence motor protection in 8.4.3.2.

6.6 Underexcitation (loss of field) protection (Device 40)

Underexcitation protection applies only to synchronous motors. The relay can monitor the rotor field winding. Loss-of-field condition affects the VAR import/export condition of a synchronous motor, and multifunction relays (Device 11) can monitor VAR flow to detect this condition.

6.7 Overexcitation (volts/hertz) protection (Device 24)

Overexcitation protection (Device 24) applies to synchronous motors and it monitors the rotor field winding. This protection also applies to induction motors in critical service, motors with local generation, motors with possible island generation, and other similar locations.

6.8 Bearing protection relay (Device 38)

A bearing protection relay monitors the bearing temperature and trips the motor when the operating temperature reaches the trip set point. In many cases, the bearing temperature alarm setting is 90 °C and trip setting is 100 °C; however, for synthetic lubricant the alarm setting is 120 °C and the trip setting is 130 °C. The settings should follow the manufacturer's recommendations.

6.9 Mechanical condition protection relay (Device 39)

Mechanical condition protection detects the occurrence of abnormal mechanical conditions such as vibration, eccentricity, expansion, shock, tilting, and/or seal failure. It uses various sensors to send signals to protection relays. See 8.5.5 for detailed description of vibration protection for MV applications.

6.10 Thermal and electronic overload protection (Device 49)

Also refer to 7.2.2, 7.4, 8.5.2, and 9.1.7.

The use of mechanical thermal overload relays is generally limited to LV NEMA Frame motor starters and legacy MV Class E2 starters. Mechanical thermal overload relays are constructed as either melting alloy (eutectic) or bimetallic. Although three-phase construction-block designs are the most common, single-phase elements might sometimes be encountered. The relays operate within a current range, as follows:

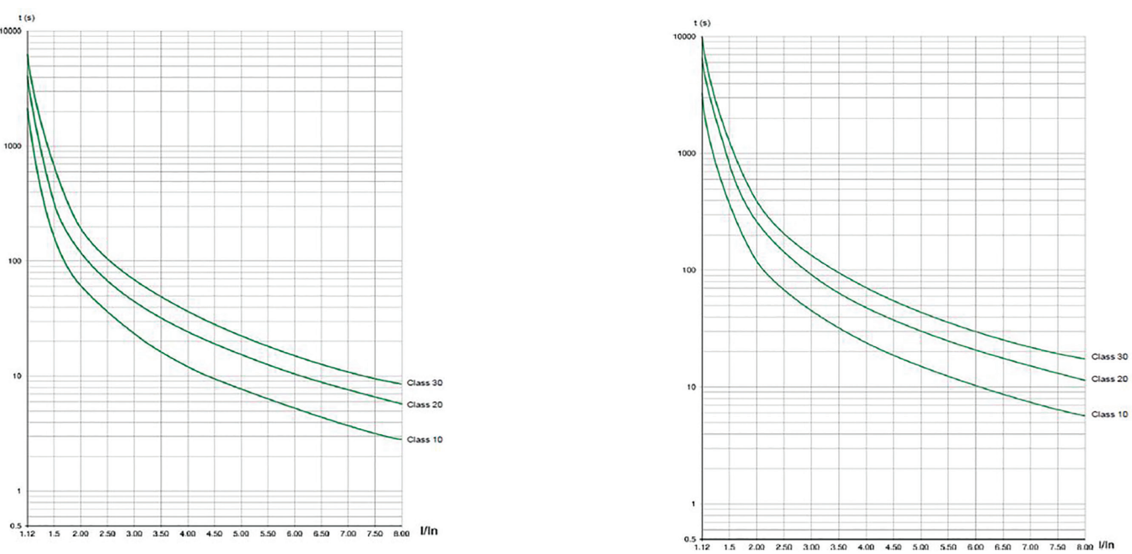
a) Selection of the heater element should be based upon the relay manufacturer's tables relating motor characteristics and ambient temperature conditions and be based on the location of the motor relative to the relay. This method is employed because only minor adjustments need to be made in the relay itself to set a trip value to match the motor current.
b) After selecting the heater, the melting alloy unit is considered non-tamperable.
c) Older bimetallic types can have limited adjustment of trip setting intended to compensate for ambient temperature. Newer relays have a wider adjustment range.
d) The thermal memory of bimetallic overload relays provides somewhat satisfactory protection for cyclic overloading and closely repeated motor starts.

e) A manual reset feature is available and is normally trip free (manual override is not possible).

f) Some relays are available as ambient-temperature-compensated or as noncompensated. Noncompensated is an advantage when the relay and motor are in the same ambient condition because the relay opening time changes with temperature in a similar manner as the motor overload capability changes with temperature.

g) NEMA ICS 2-2000 has standardized motor overload relays into three classes denoting time delay to trip on locked rotor current: Class 10 for fast trip, 10 s at six times the overload rating; Class 20, for intermediate trip, for 20 s at six times the overload rating; and Class 30 for long-time trip, 30 s at six times the overload rating. In most applications, the Class 10 relay is applied for hermetic and other motors with a service factor of 1.00 or 1.05. The Class 20 relay is commonly used for higher service factor motors, such as NEMA T-frame motors. A Class 30 relay is used in applications where high-inertia loads cause the motor to have a long starting time, such as conveyor belt motors.

h) Electronic devices for overload protection are also available. For LV motor starters, electronic devices, sometimes integral with the contactor, sense the current in all three phases. These can be adjusted for Class 10, Class 20, or Class 30. Refer to Figure 11 for typical thermal overload curves for cold condition and warm conditions, a) and b), respectively. For MV motors on NEMA E2 starters and motors controlled by circuit breakers, the 49 device protection is typically offered through the use of a multifunction motor protection device (Device 11M).



a) Thermal overload curves, cold

b) Thermal overload curves, warm

Courtesy of Schneider Electric.

Figure 11—Thermal overload curves, a) cold and b) warm

6.11 Motor bus automatic transfer or reclosing

6.11.1 Nature of problems

Automatic transfer: To maintain process continuity upon loss of power supply, motor buses may require transfer from an existing source to a new source. Another case involves the loss of a single source for a motor bus, and a decision to trip the source breaker, with the possibility of reclosing back into the same source once the source recovers. In either case, the existing source motor bus breaker is tripped before a motor bus source

breaker can be closed or reclosed. Thus, there is a period of time when the motor bus is not connected to any source, during which the motors connected to the bus begin to slow down and generate a decaying voltage and frequency onto the bus. For a transfer, if the new source voltage is healthy, or for a reclose, if the single source voltage recovers, but the source breaker is closed with the source voltage significantly out-of-phase with the motor bus voltage, then high inrush current can damage the motor windings and produce torques damaging to the shaft, foundation, drive coupling, driven equipment, and gears. However, the new source breaker can be closed or the existing source breaker can be reclosed immediately if the phase angle between the motor bus and the new source is within an acceptable angle near zero degrees or subsequently at the next synchronous pass through zero degrees.

Reclosing: When the source voltage is interrupted, initially motors continue to rotate and generate a back electromotive force (emf) which appears as voltage on the motor bus as a result of one or more motors connected to the bus. This voltage decays with motor speed and internal flux. If the source voltage is restored out-of-phase with the aggregate motor bus voltage, then high inrush current can damage the motor windings and produce torques damaging to the shaft, foundation, drive coupling, driven equipment, and gears (see 6.2).

ANSI/NEMA Std C50.41–2012, Section 14, identifies fast transfer or reclosing on a motor bus as one in which the resultant volts per hertz between the motor residual volts per hertz phasor and the incoming source volts per hertz phasor at the instant of transfer or reclosing is completed does not exceed 1.33 per unit volts per Hz on the motor rated voltage and frequency basis [B3]. The equation not only looks at the motor residual value, but also at the value of the system source and the angle between them. According to ANSI Std 50.41–2012, out-of-phase bus transfers develop transient currents and torques that may range from 2 to 20 times rated, and yet the pu V/Hz calculation ignores current, and thus cannot possibly address the torques motors are experiencing. Field studies demonstrate that significantly out-of-phase residual voltage slow bus transfers can result in a pu V/Hz below 1.33, and yet calculated torques at transfer are over 20 times normal running torque. These studies show that synchronous fast transfers are also below 1.33 pu V/Hz, but that calculated torques at transfer are consistently under 3 times normal running torque (Yalla and Beckwith [B68]). Subclause 6.4 of IEEE Std C37.96–2012 and Yalla, et al. [B67] discuss in detail how to implement safe reclosing using fast, permissive synchronizing (Device 25) and fast-closing circuit breakers. The benefit of fast synchronous transfer or reclosing is continued process operation without long, costly downtime. Both 6.4 of IEEE Std C37.96–2012 and section 14 of ANSI Std 50.41–2012 discuss the motor and connected-load damage and loss-of-life resulting from a wide range of motor and system parameters [B3].

6.11.2 Motor protection and supervision during automatic transfer or reclosing

6.11.2.1 Introduction

For detailed design information on motor bus transfer (MBT) design and protection, refer to 6.11.2.2 in this standard and 6.4 and 6.4.1 to 6.4.18 of IEEE Std C37.96–2012.

For detailed design information for design and protection when reclosing from a single source, refer to 6.11.2.2 in this standard and 6.4.19 of IEEE Std C37.96–2012. When reclosing from a single source, the following protection should be considered:

a) Delay restoration of system voltage, using a timer (Device 62) for a preset interval sufficient for adequate decay of the motor internal voltage. This method might not be as necessary if the power supplier cooperates on the reclosing, but could be a backup device.

b) Delay restoring system voltage until the internal voltage fed back from the motor(s) has dropped to a low enough value. Commonly, this value is considered to be 25% of rated voltage. Refer to 6.11.2.3 for residual voltage transfer information (ANSI/NEMA Std C50.41–2012 [B3], Beckwith and Yalla [B7], IEEE PSRC Report [B34], and Zhao, Mouton, and Sevov [B70]). The frequency also decreases as the voltage decays because of motor deceleration. The undervoltage element (Device 27) and its setting should be chosen to make the relay dropout independent of frequency. If an ac frequency-sen-

sitive relay is used, it should be set (based on motor and system tests) to actually drop out at 25% of rated voltage and at the frequency that will exist when 25% of rated voltage is reached.

c) Use a high speed underfrequency element (Device 81) to detect the supply outage and trip the motors before supply voltage is restored.

d) Use single-phase (Device 27) or three-phase undervoltage elements as follows:

    1) One element with a sufficiently fast time setting can be connected to the same VT as is the underfrequency relay [see item c)] and sense the fault condition that results in insufficient voltage to operate the underfrequency element.

    2) One, two, or three relays elements (i.e., each connected to a different phase) can be used to detect the supply outage and trip the motors when sufficient time delay exists before the supply is restored.

e) Use a loss-of-power (undercurrent) element (Device 37). This element should be sufficiently fast and sensitive. The Device 37 should be active only in the motor-running state (blocked at startup) when sufficient load is obtained on the circuit or motor.

f) Use a reverse-power element (Device 32). This relay element detects a separation between motors and the source. While this approach is suitable in some circumstances, generally the loss-of-power relay element is more suitable than the reverse-power element because of the following limitations:

    1) During the fault when the source is still connected to the motors, net power flow continues into the motors for low-level faults. Although not true for three-phase bolted faults, low-level faults have a very low impedance into which reverse power flows.

    2) Usually, tripping by reverse power is effective only if a definite load remains to absorb power from high-inertia motor drives after the source fault-detecting elements isolate the source from the motors.

    3) Reverse-power relays responsive to reactive power (i.e., VARs) instead of real power (i.e., watts) usually do not provide a suitable means of isolating motors prior to automatic reclosing or automatic transfer operations.

6.11.2.2 Protection from excessive shaft torques during transfer or reclosing

An out-of-phase bus transfer of MV and low voltage (LV) motors from one energized power system to another energized power system could cause very high motor inrush currents and severe mechanical shock to the motor. The abnormal inrush currents may be high enough to trip circuit breakers and open fuses and these currents could damage motor system components. Mechanical damage, which may occur in the motor, the coupling to the load, or the load itself, is caused primarily by excessive transient torque. Momentary voltage interruptions followed by out-of-phase reclosing on the same bus expose the motor system to the same effects. Refer to 6.4 of IEEE Std C37.96–2012 and Clause 14 of ANSI/NEMA Std 50.41–2012 for information on this potential problem [B3].

Methods to reduce this problem are detailed in 6.4 of IEEE Std C37.96–2012. Published in May 2012, a more comprehensive study of the solution to the problem can be found in the IEEE Power System Relaying Committee (PSRC) Report, “Motor Bus Transfer Applications Issues and Considerations” [B34]. It defines two independent methods that may be concurrently employed in open transition transfers, which the IEEE PSRC Report defines as “The process of transferring motor bus load from one source to another source, designed to trip the old source breaker before closing the new source breaker so that the two source breakers are open at the same time during the transfer process.” With the fast transfer method, the close of the new source breaker “is supervised to ensure that the voltage phase angle difference between the motor bus voltage and the new source voltage is within a predetermined acceptable limit” [B34]. The fast transfer method sends a breaker close command when the angle between the motors and the new source is within a phase-angle limit. With the in-phase transfer method, “the close command to the new breaker occurs at a phase angle in advance of phase coinci-

dence between the motor bus and the new source to compensate for the new breaker's closing time" [B34]. The in-phase method sends a breaker-close command at an advance angle before zero degrees to compensate for the breaker close time so that the motors are connected to the new source at zero degrees. Both methods may also be supervised by a frequency difference (slip frequency) limit. The residual voltage transfer method is not a synchronous method as it only closes at low bus voltage and ignores the phase angle and slip frequency between the motor bus and the new source. Refer to 6.11.2.3 for residual voltage transfer information (ANSI/NEMA Std C50.41–2012 [B3], Beckwith and Yalla [B7], IEEE PSRC Report [B34], and Zhao, Mouton, and Sevov [B70]).

The problem of momentary source voltage interruptions followed by out-of-phase reclosing on the same bus can also be eliminated using the fast and in-phase transfer methods. Upon voltage interruption on the source, a local source breaker can be tripped to isolate the motor bus from the source. When the source voltage is restored, these methods can be used to close the local source breaker at the next pass through zero degrees between the motor bus and the restored source.

6.11.2.3 Protection from excessive shaft torques during transfer in emergency and standby power systems

Excessive shaft torques can occur in emergency and standby power systems when a motor(s) is de-energized and then rapidly reconnected to another (or same) source of power that is out-of-phase with the motor's regenerated voltage. Motors above 37 kW (50 hp) driving high-inertia loads (e.g., crushers, shredders, fans) may require special consideration.

The problem can be eliminated if the motor circuits can be de-energized long enough to permit the residual voltage to completely decay before power is again applied to the motor. The residual voltage transfer method is not a synchronous method as it only closes at low bus voltage and ignores the phase angle and slip frequency between the motor bus and the new source. Some undervoltage functions, Device 27, used for residual voltage transfers, may not be able to maintain its set point accuracy at the low frequencies typically experienced during residual voltage transfers (Zhao, Mouton, and Sevov [B70]). This could result in voltage transfers at a higher or lower voltage than anticipated. The residual voltage transfer method exposes motors to a 50% probability that the close angle at transfer will exceed the 90 degree maximum phase angle specified by ANSI/NEMA Std C50.41–2012 [B3]. Field results indicate that at 25% voltage, with an out-of-phase close, the motor rotor flux linkages may not have decayed sufficiently, and that the transient current and torque associated with the bus transfer or reclosing may not remain within acceptable levels (Beckwith and Yalla [B7]). Additional information is found in 6.4 of IEEE Std C37.96–2012 and in the IEEE Power System Relaying Committee Motor Bus Transfer Report [B34].

An open circuit time delay is used to identify when the motor's voltage has decayed to a level where damaging torques will not occur, which varies depending on the motor. See Annex E for information on calculating one open circuit time constant. This step can be done in two ways. In one method, auxiliary contacts or a relay on the automatic transfer switch can open the motor holding coil circuits, while the transfer is delayed several open circuit time constants (typically about 3 s to 10 s). This method can be effective and requires interwiring between the transfer switch and the motor starters and depends upon the reliability of a timing device. Another method uses a transfer switch with a timed center-off position. The switch opens, goes to the off position, remains off several open circuit time constants (typically about 3 s to 10 s), and then completes the transfer. This approach eliminates any interwiring to the motors. The required time delay should be set carefully and varies as system conditions change. A third position (neutral) creates the danger that the transfer switch might remain indefinitely in the off position in the event of a control circuit or contactor malfunction.

Another solution is to parallel momentarily the two power sources on transfer, connecting both sources together, and then dropping one. The two sources may not be derived from the same primary source and might have a large standing phase angle between them, preventing a hot parallel transfer. This approach is completely effective because power to the motors is never interrupted. However, it can require new equipment. If one source is utility power, utilities that permit paralleling another source with their systems will require additional protec-

tive relaying per IEEE Std 1547™-2003 IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems [B30]. In obtaining permission for the paralleling from the utility, a design review can lead to additional protective relaying. An additional factor is that the combined available fault current may exceed the ratings of the connected electrical switching equipment. This is defined as a closed transition (hot parallel) transfer and is only recommended for manual transfer and not for automatic transfer (emergency) operation under fault conditions. Exposure to double-fed faults during parallel operation may violate the interrupt rating of the circuit breakers or the through-fault withstand ratings of source transformers and damage connected equipment. The design should consider that a parallel condition is temporary and breaker failure is a concern.

For breaker failure protection information, refer to:

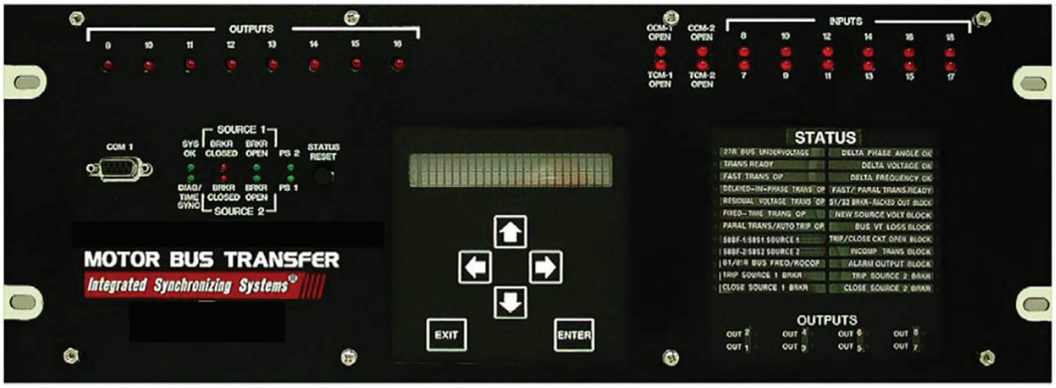
— IEEE Std C37.96–2012, 6.4.1.1

— IEEE Std C37.119–2005 [B32]

— IEEE PSRC Report, “Motor Bus Transfer Applications Issues and Considerations” [B34]

When motors are de-energized, the motors’ regenerated voltage may rapidly move out-of-phase with the other source of power. The combination of the synchronous fast and in-phase transfer methods is another solution to the problem. These methods are implemented with special-purpose motor bus transfer relays that are able to track in real time the initial phase angle between the motors and the other source, and immediately after the motors are de-energized, track the instantaneous phase angle and frequency decay of the motors compared to the other source. Refer to Figure 12 for an example of a motor bus transfer system. If the initial phase angle is small, and it is determined that the breaker close time will be able to complete the reconnect before the angle becomes excessive, the fast transfer method will immediately initiate breaker closure. However, if the initial angle and subsequent increase in phase angle and frequency decay of the motors exceed set limits, such that a fast transfer is blocked, then the in-phase method takes over and closes at the next pass through zero degrees. This method compensates for breaker close time and the frequency decay to ensure that the motors are reconnected in phase with the other source of power.

Synch-check relays or automatic synchronizers that monitor the phase-angle difference between two power sources (Device 25), but are only designed to supervise generator synchronizing or transfer switch operation, exhibit response times much slower than are required for motor bus transfer (IEEE PSRC Report [B34]). They are not able to track the rapid phase angle and frequency decay of the de-energized motors, which results in the out-of-phase re-connect and excessive shaft torques that can occur in emergency and standby power systems. Furthermore, typical transfer switches with transfer times of 10 cycles (167 ms) are unacceptable for the implementation of a motor bus transfer scheme. Upon motor de-energization, even at a medium inertia frequency decay of 20 Hz/sec (R_S), the angle movement ($\Delta Ø$) in 10 cycles (T), per the equation $\Delta Ø = 360 \times 0.5 R_S T^2$, is 100°. So in the optimal case where the initial angle is 0° between the motors and the other source, by the time the transfer switch finally completes the transfer, the phase angle at close would be a damaging 100°.



Courtesy of Beckwith Electric.

Figure 12—Multifunction motor bus transfer system, Devices 25, 27, 50, 50BF, 60FL, 81

6.11.2.4 Contactor considerations for motor bus transfer and reclosing

Motor contactors should be designed to hold in during automatic synchronous motor bus transfers.

6.12 Multifunction relay (Device 11)

6.12.1 Introduction

An important development has been the multifunction motor protection relay. Recognized as a powerful tool, the multifunction relay incorporates many protective functions that normally would be applied through the use of separate protective relays. With the multifunction relay all protection elements are incorporated into one enclosure. For example, the multifunction relay provides short-circuit and overcurrent protection for each phase, all phases together, and for ground fault protection. Depending upon the options selected, the relay could include protection against stalls, locked rotor, overtemperature alarm and/or trip, current unbalance, metering, and communication. No detailed discussion of the relay is included in this subclause because the possible functions are described under other protective relays, such as Device 50 and Device 51.

The 1-line and 3-line diagrams showing protective device functions can use the Filled Box method (as illustrated in this standard) or use the List Box method described in IEEE Std C37.2–2008 Figure A.2 and Figure A.3, respectively.

6.12.2 Device 11, MV multifunction relay applications

A multifunction relay can protect a MV motor starter with a vacuum contactor. While a bimetallic thermal overload relay could be used, as is done for many low-voltage motors, a greater measure of protection is usually desired for MV motors because of the cost and the critical role of these motors in many applications.

As shown in Figure 7 and Figure 8, fused MV starters with contactors are used in some applications. The MV starter consists of a contactor (commonly vacuum contactor, others are air, SF_6, or oil-filled) protected by multifunction relay and fuses. For some users, a MV circuit breaker is the preferred device for starting and stopping motors, particularly for infrequent starting and larger motors as shown in Figure 19 and Figure 20.

Formerly, separate devices may have been used for various protective functions. Several of these are noted earlier in this document: instantaneous overcurrent Device 50, time overcurrent Device 51, and undervoltage Device 27. While offering adequate protection, these devices occupied significant space, required considerable labor to mount and wire, and required calibration and maintenance for each relay. Whether MV starters or

MV breakers are used for motor starting, the same multifunction relay can be used with either device to effect motor protection.

Modern multifunction relays offer protective and monitoring features impossible in older electro-mechanical devices. Arc flash sensing is now being incorporated into some multifunction relays. Waveform capture, starts-per-hour protection, fault data logs, broken rotor-bar detection, trending, and motor load profiling are some of the diagnostic and monitoring functions available. Modern multifunction relays model the thermal state of the motor (see 8.2) using a thermal model (Device 49). Generally, thermal capacity (TC) calculations in the relay match the motor damage curves closer than simple overcurrent-protection curves.

Usually, multifunction relays provide operator interface panels, consisting of LCD screens with soft function keys that are used for setup and for scrolling through the parameters. Figure 13 shows a multifunction motor protection relay, Device 11M. Most multifunction relays offer configuration software. By using software, a user can setup motor protection from a computer, upload new setups, download and save files, and monitor the relay locally and remotely. Most relays have Boolean logic capability (AND, OR, NOR gates) programmable via the software. Second-generation motor relays have all Boolean functions, and configuration is by dragging symbols and interconnecting these with a computer mouse.

Courtesy of Basler Electric Company.

Figure 13—Multifunction motor protection relay, Device 11M

Additional input/output capacity may be standard or optional for starter auxiliaries. Motor and bearing RTD inputs, formerly requiring a separate relay, may be available.

Many installations benefit from communications capability incorporated into protective relays. Communication capabilities allow interfacing with the software package for setup, troubleshooting, and monitoring. Communication also allows remote monitoring of motors for operating status, operating current, fault history, and others. Older, separate relays did not generally include communications. Communications can be accomplished via RS-232, USB, and Ethernet through fiber ports and copper-wire connections. Protocols can be Modbus RTU, Modbus TCP, IEC 61850, and others.

Device 11M is often used in MV ASD applications as discussed in 9.3.

6.12.3 Device 11, LV multifunction relay applications

Historically, protection for LV motors was provided by heaters in bimetallic overload relays or by solid-state overload relays. Today, many users want greater protection. Multifunction relays are available for this purpose.

In addition to overload protection, multifunction relays provide low-current (and low-power) protection for pumps to provide cavitation protection, jam and stall protection, frequency-of-start protection, ground fault protection, and others. Arc flash sensing is now being incorporated into some multifunction relays.

Multifunction relays typically provide a human machine interface (HMI) panel through which setup and monitoring are accomplished. Fault-type, cause of fault, run/stop status, running current, and other parameters can be read from the display. Remote HMI ports might be offered for mounting in motor control centers and enclosed starter enclosures.

Multifunction relays can also include, as standard or optionally, RTD inputs and additional analog input/output points. Input/output points can be used to interface with external control, reversing, multi-speed, and reduced-voltage starting systems.

Some applications require communications. While traditional overload relays have not included communication, many multifunction relays either include communication in the standard feature-set or offer it optionally. Communications available include RS-232, RS-485, Modbus RTU, Modbus TCP, IEC-61850, Ethernet, and others.

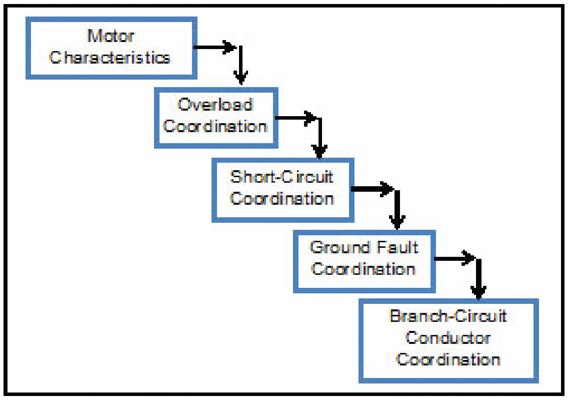
Device 11M can be used in LV ASD applications as discussed in 9.2.

7. Low-voltage (LV) motor protection

7.1 Introduction

Conventionally, LV motors drive small process equipment and auxiliary equipment. These motors can operate continuously and may be in cyclical services. These applications use motor contactors in motor control centers (MCCs) or combination starters. Refer to IEEE Std 1683™ for information on reducing electrical hazards in MCCs up to 600 V ac. Refer to UL 845 for MCCs. Refer to IEEE Std C37.13™ for low-voltage power circuit breakers, IEEE Std C37.17 for low-voltage power circuit breaker trip systems, IEEE Std 1015-2006 (*IEEE Blue Book*™) for low-voltage breakers, and UL 489 for molded-case circuit breakers [B64]. Refer to NEMA ICS 2 for controllers, contactors, and overload relays. Also see Nailen, "Managing Motors" [B40].

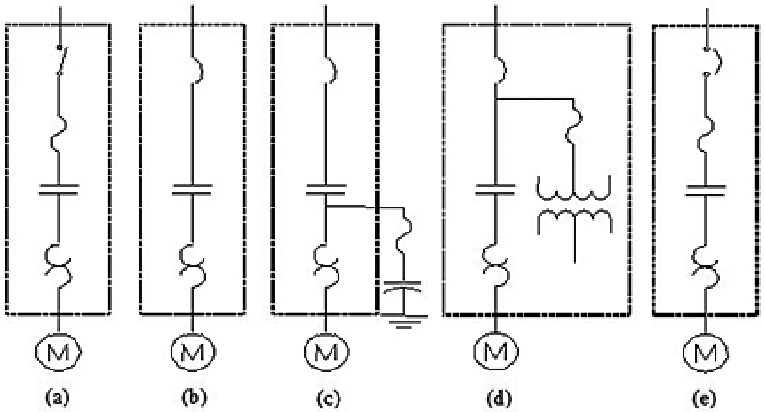
For LV motor protection, motor coordination studies are broken into five main areas, which are shown in a simplified flow chart in Figure 14. Data and device selections from each area flow forward and are used to achieve protection and selectivity at the next area. As each area of protection is analyzed, the protective device curves are added to the coordination plot, which is a time-current plot on a log-log graph. A typical coordination plot for a low-voltage motor application is in Figure 16.



Courtesy of Padden Engineering, LLC.

Figure 14—Five main areas of LV motor coordination studies (Padden and Pillai [B48])

One-line diagrams of typical LV starters for industrial applications using MCCs or combination starters are shown in View (a), View (b), View (c), View (d), and View (e) of Figure 15.



Courtesy of Padden Engineering, LLC.

a) Typical starter with fuses

b) Typical starter with a circuit breaker

c) Typical location for power factor correction capacitors

d) Typical location for control power transformer

e) Typical starter with molded-case switch and fuses

Figure 15—Typical LV starter one-line diagrams for industrial applications using MCCs or combination starters

7.2 Low-voltage motor overcurrent protection

7.2.1 Introduction

Overload protection for LV motors is usually provided by thermal overcurrent relays or electronic over-current devices. In some cases, dual-element fuses or a thermal-magnetic circuit breaker may serve as the

primary overload devices, but are normally backup protection for overload relays. Short-circuit protection for low-voltage motors is usually provided by fuses, a thermal-magnetic circuit breaker, or an instantaneous trip device (or motor circuit protection) in combination with an overload relay. Ground fault protection for low-voltage motors is usually provided by the short-circuit protection device, but ground fault relays may be installed. (See Bradfield and Heath [B8], Gregory and Padden [B14], [B15], Nailen [B41], and Smith [B58].)

7.2.2 Thermal and electronic overload relays

Overload relays are sized in accordance with the NEC. NEC Section 430.32 references the motor nameplate rating. Power factor correction capacitors installed for individual motors may be connected as shown in View (c) of Figure 15, and no current adjustment need be made to the overload devices. However, this connection is not the only method of providing individual power factor correction and has been known to cause contactor failures due to resonance with other motor capacitors (see 5.13 and Nailen [B41]). When capacitors are installed between the overload device and the motor, the overload relay provides circuit impedance, which generally dampens the resonance problem. However, the overload relay current rating should be adjusted to account for the reduced current flowing to the motor-capacitor combination (see NEC 460.8 and 460.9). Part 14.43.3 of NEMA MG-1-2011 recommends a bus connection when several motors are connected to the bus to reduce the potential harmonic resonance.

Overload relays and other devices for motor overload protection that are not capable of opening short-circuits shall be protected by fuses or circuit breakers with ratings or settings in accordance with NEC Article 430.52 or by a motor short-circuit protector in accordance with NEC Article 430.52 (see NEC 430.40).

7.2.3 Time-delay (or dual-element) fuses

Time-delay (dual element) fuses are available from 0.1 A through 600 A. Fuses for short-circuit and ground fault protection shall be sized in accordance with NEC Article 430.52 and its Table 430.52. The full load current values used for that table are in Table 430.248, Table 430.249, and Table 430.250. The rating of a time-delay fuse shall be permitted to be increased, but in no case exceed 225% (400% for Class CC fuses) of full load current. A one-line diagram of a typical starter with fuses is shown in View (a) of Figure 15. Also available are fuses without time delay, which can provide short-circuit and ground fault protection, but may not provide any backup protection.

7.2.4 Inverse-time circuit breakers

These circuit breakers (i.e., molded case) are available from 10 A through 3000 A when constructed with thermal-magnetic trip elements, and up to 5000 A when constructed with solid-state trip elements. Both types of trip devices are referred to in the NEC as inverse-time circuit breakers and shall be sized in accordance with NEC Article 430.52 and Table 430.52. The full load current values used for that table are in Table 430.248, Table 430.249, and Table 430.250. The rating of an inverse-time circuit breaker shall be permitted to be increased, but in no case exceed, the following:

— 400% for full load currents of 100 A or less

— 300% for full load currents greater than 100 A

A one-line diagram of a typical starter with a circuit breaker is shown in View (b) of Figure 15.

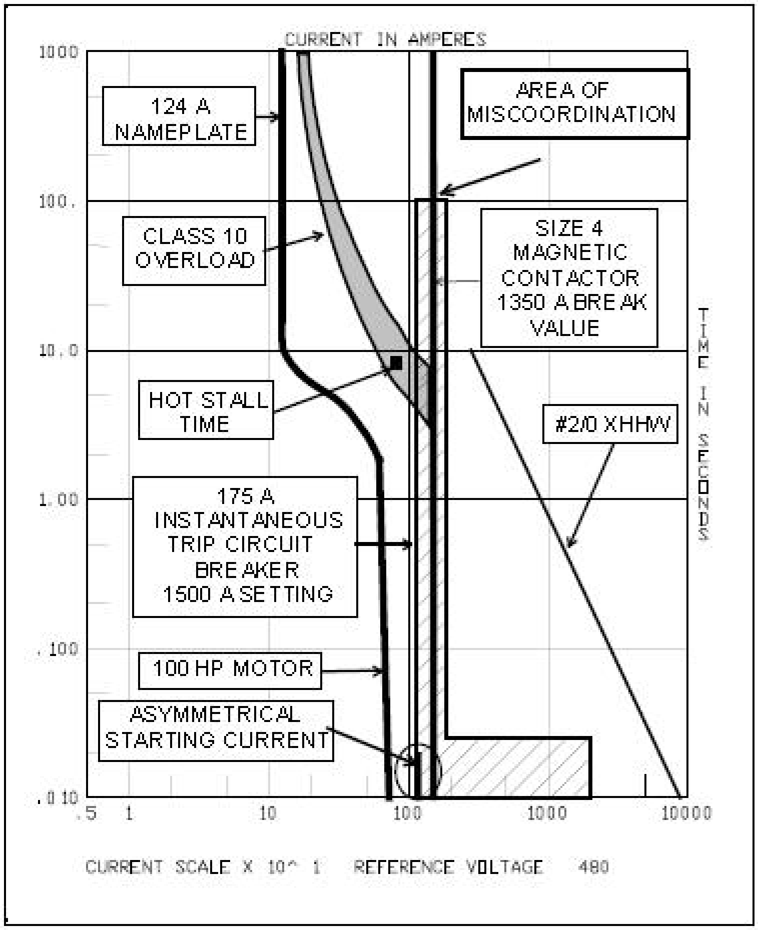
7.2.5 Instantaneous trip circuit breakers

Instantaneous trip circuit breakers (i.e., molded-case) are available from 3 A through 1200 A. The instantaneous setting can typically be adjusted in fixed steps to between 3 to 13 or 3 to 10 times the continuous-current rating. Instantaneous trip circuit breakers are tested under UL 489 [B64]. The trip range of the breaker should be within +30% or –20% of the set point. On the coordination plot, these devices have a broad bandwidth corresponding to these tolerances.

These breakers are referenced as instantaneous trip breakers and shall be sized in accordance with NEC Article 430.52 and Table 430.52. The full load current values used for that table are in Table 430.248, Table 430.249, and Table 430.250. Trip settings above 800% for other than Design B energy efficient motors and above 1100% for Design B energy efficient motors shall be permitted where the need has been demonstrated by engineering evaluation. In such cases, it shall not be necessary to first apply an instantaneous trip circuit breaker at 800% or 1100%. An adjustable instantaneous trip circuit breaker shall be used when it is part of a listed combination controller having coordinated motor overload, short-circuit, and ground fault protection in each conductor and if it operates at not more than 1300% of full load motor current for other than NEMA Design B energy efficient motors and no more than 1700% of motor full load current for Design B energy efficient motors. A one-line diagram of a typical starter with a circuit breaker is shown in View (b) of Figure 15.

Two points should be reviewed by the engineer. First, the overload device is normally the only line of protection from overloads and high-impedance faults when using instantaneous trip circuit breakers. A failure of the overload device, the overload wiring, or the contactor can prevent the circuit from being isolated due to overload or high-impedance fault conditions. Where backup protection is desired for these abnormal conditions, an inverse-time circuit breaker or dual-element fuses should be selected.

Second, the selection of the contactor and conductor sizes depends on the setting of the instantaneous trip function. NEMA rated magnetic contactors are tested to break up to 10 times the full load current values given in NEC Table 430.248, Table 430.249, and Table 430.250 for the corresponding horsepower rating of the contactor. When an overload device trips, the contactor is called upon to open the circuit. Therefore, the contactor should be rated to break the circuit. Under high-impedance fault conditions, the current may be in the range of 10 to 17 times the motor full load current. The instantaneous trip breaker may be set above the 10 times full load current break test value of the contactor. Refer to Figure 16 for the time-current curves of a 480 V, 100 hp motor application with a 175 A instantaneous trip breaker, a Class 10 overload, and a NEMA size 4 magnetic contactor (i.e., 1350 A break rating). Figure 16 illustrates a case where the instantaneous trip is set about 12 times the full load current of 124 A at 460 V (see NEC Table 430.250). The #2/0 AWG XHHW conductor is rated for 175 A at 75 °C. The contactor is not protected using the setting of about 1500 A. A lower instantaneous setting would protect the contactor, but some motors may trip the breaker on starting. Each controller shall be capable of starting and stopping the motor it controls and interrupting the locked rotor current of the motor (see NEC 430.82). Controller ratings shall meet NEC 430.83 requirements. The disconnecting means shall have an ampere rating not less than 115% of the full load current rating of the motor (see NEC 430.110).



Courtesy of Padden Engineering, LLC.

Figure 16—Time-current curve for a 100 hp motor with size 4 contactor, Class 10 overload, and an instantaneous trip circuit breaker with a setting of 12 times full load current

In Prabhakara, et al. [B50], the authors reveal that some high-efficiency motors draw up to 2.83 times locked rotor current during starting, and they recommended a 19.2 times full load current on the instantaneous breaker setting, approximately 3 times locked rotor current in one case. A typical value used in the industrial applications is 1.76 times locked rotor current for estimating asymmetrical inrush current. To reduce or prevent false tripping of the instantaneous trip breaker on starting, two options are typically used:

a) Specify a contactor with a higher break rating and set the instantaneous breaker at a higher setting within the NEC limits.

b) Use an inverse-time circuit breaker in place of the instantaneous trip breaker so that the instantaneous setting, if available, can be set above the motor inrush current.

NOTE—Thermal magnetic MCCB, insulated case circuit breakers, and LV power circuit breakers can be purchased with fixed or adjustable trip elements and digital trip units for coordinating closely with the motor capabilities.

7.3 Low-voltage motor ground fault protection

7.3.1 Introduction

Many LV motor applications utilize fuses or MCCBs for ground fault protection. However, the type of protection selected is dependent upon the type of system grounding.

7.3.2 Solidly grounded systems

Fuses and circuit breakers normally provide adequate ground fault protection for motors on solidly grounded systems. However, for larger motors applications, such as the 100 hp motor shown in Figure 16, miscoordination occurs. For example, this motor is protected by an instantaneous only circuit breaker set at 1500 A trip. The main breaker ground trip is set at 1200 A, the maximum allowed by NEC Article 230.95, where a shutdown does not introduce additional hazards. Miscoordination can occur in the region between the ground trip device on the main low-voltage power circuit breaker (LVPCB) and the instantaneous trip circuit breaker protecting the motor. LVPCBs, specified with long-time and short-time functions only (i.e., no instantaneous element), can usually be coordinated selectively.

If selectivity between the individual motor protective device and the main breaker is desired for ground faults, additional protective devices should be installed for the larger motors or interlocking ground fault devices should be installed. For solidly grounded systems, the protective devices should be wired to open the breaker, not the contactor, unless the contactors are rated high enough to interrupt the available fault current. Some breakers have integral solid-state devices that sense ground faults and open the breaker. Contactors may also have integral solid-state devices that sense ground faults, but these may open the contactor and the rating must be verified. Also, zero sequence current transformers (CTs) and trip units can be installed to shunt-trip the circuit breakers or switch, provided that the circuit breaker or switch has a shunt trip included (shunt trips are usually special order, not standard).

7.3.3 Low resistance grounded systems

Low resistance grounded systems are not normally used on LV applications because ground fault currents may not be high enough to operate the protective devices.

7.3.4 High resistance grounded systems

For high resistance grounded systems, where the fault current is usually 5 A to 10 A range, no separate motor ground fault protection is generally provided. Instead, an alarm at the grounding resistor signals that a ground fault has occurred. A ground pulsed signal is used to locate the fault. The faulted circuit is then manually cleared. Caution should be used when selecting conductor insulation materials and ratings for use on high resistance grounded systems, particularly on smaller conductors (e.g., size 10 AWG and below) because the small conductor size and insulation thickness are difficult to provide insulation rated for the line-line voltage stresses for prolonged high resistance ground fault exposure.

Some modern motor controllers provide ground fault sensing in the solid-state (electronic) overload relays or multifunction motor protection relay. Removal of the first ground fault is important to prevent escalated damage from a second ground fault on a different phase. Protective devices such as MCCBs used in high resistance grounded systems must be rated for line-to-line voltage (e.g., 480 V not 480/277 V for a 480 nominal system voltage). Also the single-pole interrupting rating should be checked to clear the second fault on a different phase: ground as well as line-to-ground faults on two separate phases, one on each side of the breaker. See Gregory [B13].

7.4 Low-voltage motor stator winding overtemperature (Device 49S)

7.4.1 Introduction

The purpose of stator winding overtemperature protection is to detect excessive stator winding temperature prior to the occurrence of motor damage. In low-voltage motors in non-critical services, the temperature sensors are normally wired to trip the motor control circuit and open the contactor.

7.4.2 Thermostat winding overtemperature devices

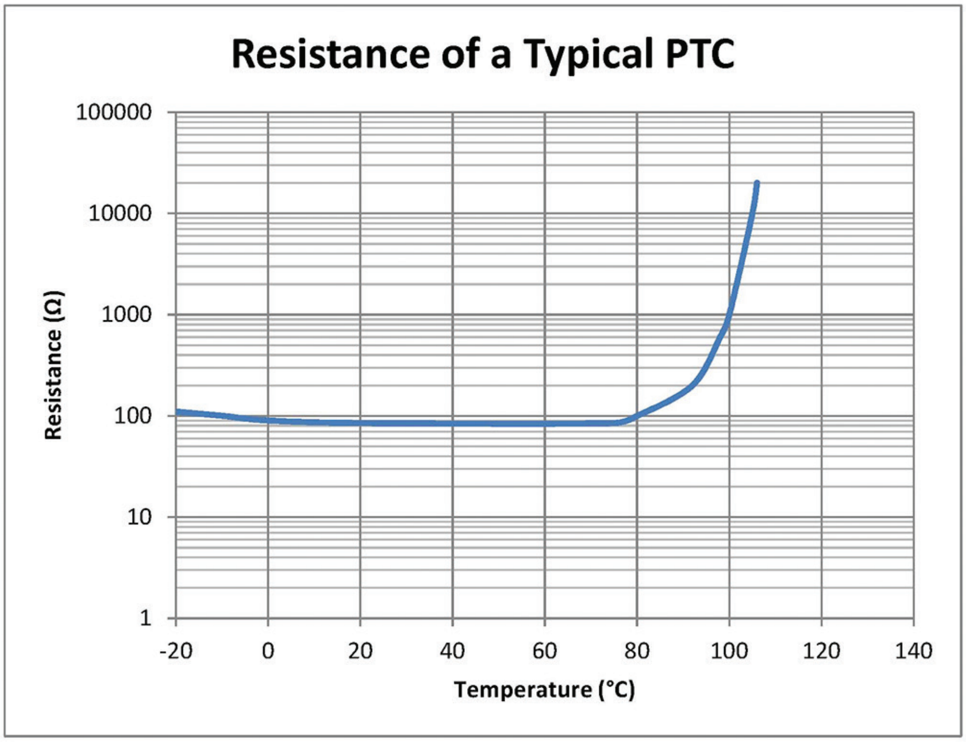
Thermostats are the most common type of stator temperature sensors installed in three-phase industrial service 460 V motors from 11 kW through 150 kW (15 hp through 200 hp). Many manufacturers wind the stators with the devices installed and cut off the leads if a customer does not specify the protection. Thermostat devices are bimetallic, normally closed devices (or normally open devices) that operate at one fixed temperature. They are normally wired in series with the control circuit at 120 V. These devices are normally sealed from the atmosphere, but are not rated as hermetically sealed for hazardous (Classified) NEC Class I, Division 2 areas.

7.4.3 Thermistor winding overtemperature devices

Thermistors are used to operate relays for either alarm or trip functions, or both. They have resistance characteristics that are nonlinear with respect to temperature and thus are not used to indicate temperature. Thermistors must match the control device. Two types of thermistors exist:

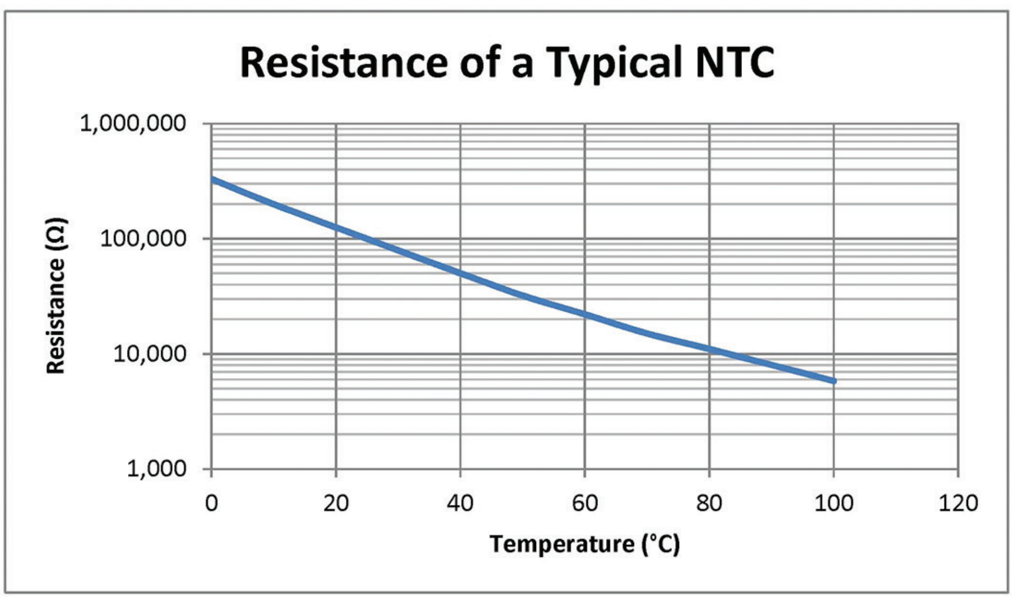
Positive temperature coefficient (PTC). The resistance of a positive temperature coefficient thermistor increases with temperature. An open circuit in this thermistor appears as a high-temperature condition and operates the relay. This arrangement is fail-safe. As shown in Figure 17, at 100 °C, this PTC type thermistor has a resistance of 1 kΩ.

Negative temperature coefficient (NTC). The resistance of a negative temperature coefficient thermistor decreases as temperature increases. An open circuit in this thermistor appears as a low-temperature condition and does not cause relay operation. This device primarily monitors temperature rather than operating a relay for protection. Refer to Figure 18 for a typical NTC characteristic thermistor.



Courtesy of Schneider Electric.

Figure 17—Typical PTC characteristics



Courtesy of Schneider Electric.

Figure 18—Typical NTC characteristics

7.4.4 Resistance temperature detector (RTD) winding overtemperature devices

RTDs may be considered in larger or critical service low-voltage motors. In those cases, the RTDs are usually connected into a device that provides an alarm and/or trip functions. The most common practice is to install six RTDs, two per phase, of the 100 Ω platinum elements class B to IEC 60751 for small motors and 100 Ω platinum element class A to IEC 60751 for large or important motor [B21]. More information on RTDs is contained in 8.5.2.2.

7.5 Low-voltage motor undervoltage protection

7.5.1 Introduction

Undervoltage protection is used to protect motors from several damaging conditions: low voltage due to a voltage sag, automatic reclosing or automatic transfer, and power restoration. In a voltage sag, the motor draws more current than normal and has unusually high heating. Excessive heating can be a serious problem in hazardous (Classified) locations and is discussed in Clause 11.

When the supply voltage is switched off during automatic reclosing and transfers, the motors initially continue to rotate and retain an internal voltage. This voltage decays with motor speed and internal flux. If the system voltage is restored out of phase with a significant motor internal voltage, high inrush can occur. Such current can damage the motor windings or produce torques damaging to the shaft, foundation, drive coupling, or gears. IEEE Std C37.96–2012 discusses considerations for the probability of damage occurring for various motor and system parameters.

When power is restored after an outage, the starting sequence should be programmed so that all motors on the system are not starting simultaneously. This step is important for the generating equipment, as well as for transformers and conductors. Undervoltage devices are not normally installed on essential loads such as motors for fire pumps.

7.5.2 Undervoltage relays

Low-voltage undervoltage relays are typically electronic devices that monitor all three phases. These devices can be furnished with a time delay to trip, a time delay to restart, or instantaneous for trip and restart. Usually, the designer sets the device at 85% of line voltage with a time delay off and a time delay for restart. Normally, the undervoltage relays are wired into the motor control circuit to open the contactor.

7.5.3 Undervoltage sensors for circuit breakers

Some MCCBs are available with an undervoltage release (UVR) that trips the circuit breaker on a low-voltage condition. The circuit breakers are required to be reset manually. Where automatic restart is necessary, this method should not be used.

8. MV motor protection

8.1 Introduction

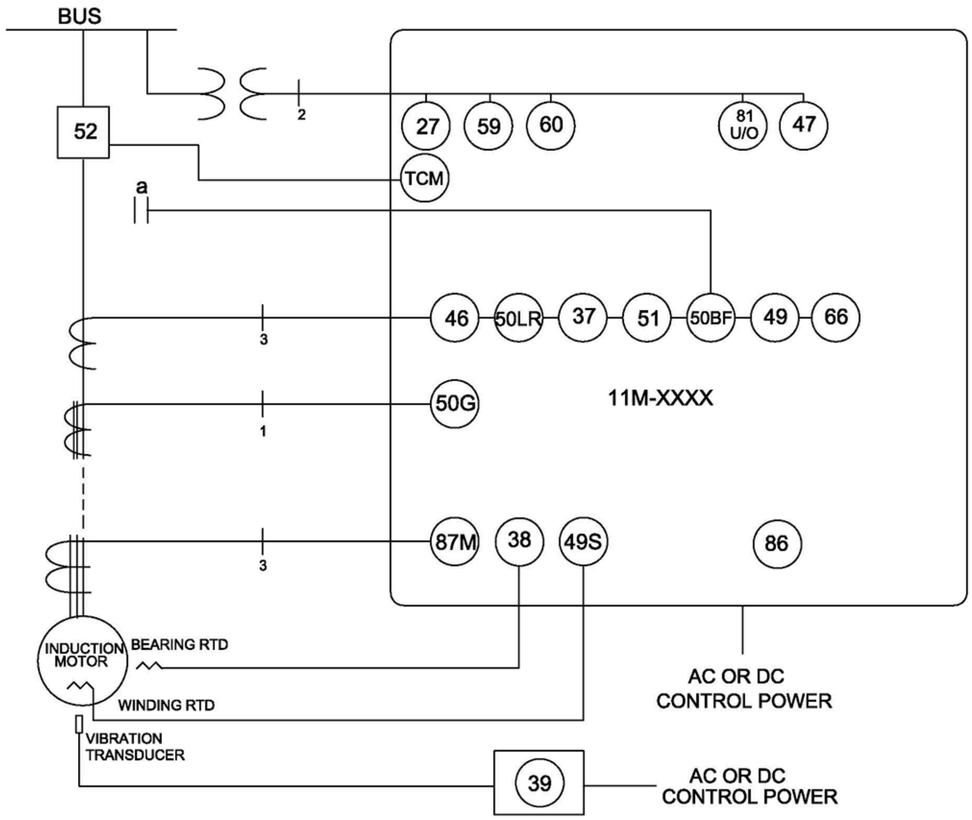
Conventionally, large motors drive the main process equipment, and typically these motors operate continuously for long periods of time, sometimes years between unit shutdowns. To control stopping and starting, MV circuit breakers are often used to apply the power to the large motors. MV motor voltage ratings are 2300 V, 4000 V, 6600 V, and 13 200 V per Part 20.5 of NEMA MG 1. When a motor must be started frequently, it might be necessary (even economical) to use motor contactors in a combination controller with a current-limiting fuse (illustrated in Figure 7 and Figure 8) rather than a circuit breaker (illustrated in Figure 19 and Figure 20) because of the greater life of the contactors.

Use care when applying MV fused motor controllers on solidly grounded wye systems because the contactor may not be rated to interrupt high fault currents, including ground faults. A comparison of the available fault currents of the power system where the controllers are applied to the fault current capability of the contactor within the controller should be done. When the contactors are not sufficiently rated to interrupt the fault currents at the point of application of the controller, ground fault relays and differential relays should not open the contactor. These protective devices should be time delayed until the fuses ahead of the contactor have time to clear the fault, or the relays should trip an alternate upstream device that is rated to interrupt the fault current. Each manufacturer performs short-circuit tests on their combination controller to confirm safe performance of the components when interrupting faults on the system to prove it will handle faults below its rated level. As a result, ground fault relays and differential relays should not open the contactor unless rated for the available fault current.

In principle, protecting MV motors is similar to LV motors, but the requirements are more demanding. Often being closer to the utility source, MV motors are more susceptible to voltage sags and surges, reclosing, and higher available fault levels. Because of the higher bus voltage and load currents, instrument transformers are used to reduce these currents to lower values used with protective relays. The most common instrument transformer secondary ratings for voltage transformers (VTs) are 120 V (line-to-line) in North America while other voltages are typical for certain regions for example 100 V (line-to-line) and/or 110 V (line-to-line) in other parts of the world. The most common instrument transformer secondary ratings for current transformers (CTs) are 5 A in North America while certain other regions use 1 A. Specific facilities can also include several different ratings, therefore it is critical for the coordination engineer to clearly identify the VTs, CTs, and relay ratings. CTs should be selected according to specifications of the motor protection relay to improve precise protection relay performance. The relay manufacturers provide CT specifications in relay manuals; these should be observed. CTs should provide the saturation-free time needed for relay operation. CT performance for distance protection can have very extreme requirements. CT matching (manufactured in the same batch) and saturation-free time are important for differential protection sensitivity and settings to reduce misoperation. CT saturation-free time is also important for overcurrent protection and other protection functions, especially when direction features are used. For example, because of missing zero crossings the directional decision might be wrong in case of CT saturation. See IEEE Std 3004.1 and IEEE Std C37.110™ for additional information on CT and VT selection and performance. Typically, the fuses or circuit breakers (i.e., air, sulfur hexafluoride [SF_6], vacuum), instrument transformers, and protective relays are mounted in switchgear. Refer to IEEE Std C37.46™ for fuse specifications above 1000 V. Refer to UL 347 for contactors, controllers, and control centers for MV. Refer to IEEE Std C37.06™ for circuit breaker ratings and capabilities above 1000 V. Refer to IEEE Std C62.21™ for application of surge protection on motors 1000 V and greater.

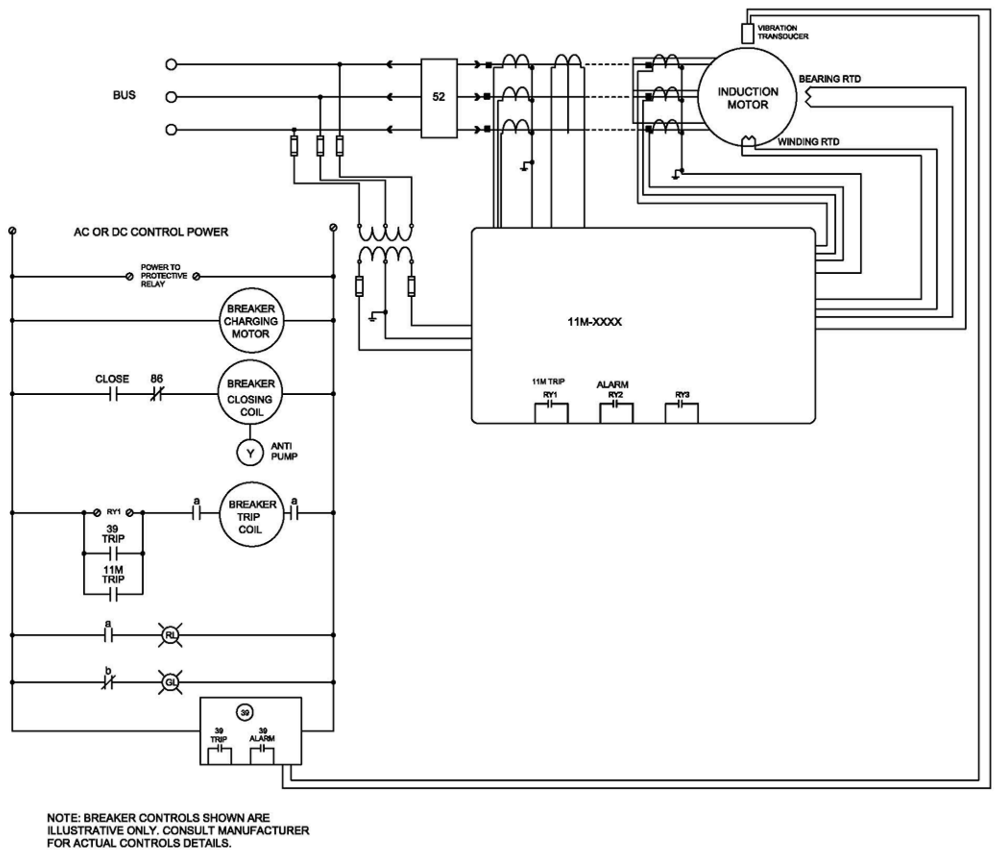
Refer to Figure 19 and Figure 20 for typical 1-line and 3-line diagrams of MV induction motor protection using a circuit breaker. The critical service protection functions from Table 6 are illustrated using a multifunction motor protection relay, Device 11M. Device 11M sends a signal to trip the breaker for various conditions, including short-circuit protection.

For MV breaker control power, dc power is preferred when applying protective relays that need auxiliary control power, or apply a UPS to back up relay control power if ac control power is used. Use capacitor trips for the breaker trip coil when control power is ac.



Courtesy of C&I Engineering.

Figure 19—MV induction motor protection 1-line diagram, Device 11M, critical service protection functions, with breaker



Courtesy of C&I Engineering.

Figure 20—MV induction motor protection 3-line diagram, Device 11M, critical service protection functions, with breaker

8.2 MV motor thermal overload protection (Device 49)

Motors generate heat while running. Using an accurate model of the motor heating (using equivalent motor current) yields benefits in using the motor to maximum effect without damage.

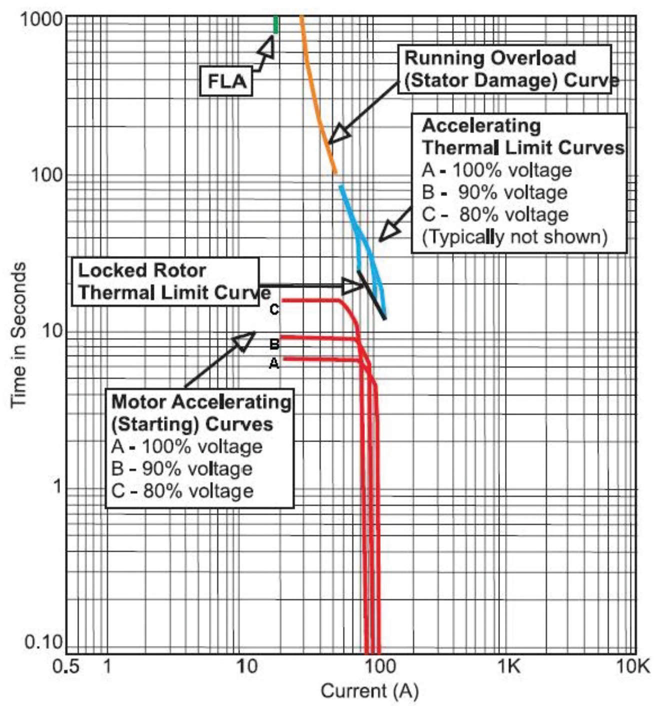
NOTE—Primary and secondary coolant flows (i.e., air, water, and other mediums) affect motor temperature. Electric motors need some type of cooling when they are running to remove heat that is created by losses. The cooling medium of a running motor depends on the type of motor enclosure that is employed. There are a number of different types of motor enclosures and the cooling is impacted in various ways depending on the enclosure design. The motor/model cooling time constant may vary with the cooling media. Information on motor time constant should be available from the manufacturer.

Thermal protection of a motor is vital to motor longevity. Rule of thumb: for every 10 °C rise in temperature, motor insulation life is cut in half. Older motor protection methods used overcurrent 50 and 51 elements instead of the 49 thermal model (Device 49) and had no backup resistance temperature detector (RTD) devices (49S). Comparing these two methods of motor protection (Device 50/51 and Device 49), demonstrates the benefits of the Device 49 thermal model for motor protection versus using an overcurrent method (Ransom and Hamilton [B51], Schweitzer and Zocholl [B55]). Compromises generally occur when employing overcurrent protection because typical 50/51 element curves do not match motor damage curves and do not take negative sequence current effects into account.

For cyclic overloads (for example, crushers, conveyor-belt motors), thermal model Device 49 protection is generally superior to overcurrent-based protection because the thermal-model protection more closely models the Thermal Capability curves of the motor. During an overload, motor heating is a long-term effect—it takes time to raise the temperature of the motor mass. The thermal model tracks this heating and allows temporary overload operation. Overcurrent protection trips too quickly, before the motor has reached a critical temperature. Once the overload cycles to a less-loaded state, the thermal model tracks the resultant motor cooling.

A motor thermal model uses an *equivalent current*, I_{eq}, calculation that represents the actual motor flux dynamics. This equivalent motor current accounts for the heating effects of negative sequence and other currents present in motor applications (IEC 60255-149:2013 [B20]).

Using thermal overload protection may extend motor life and allow efficient usage of motor capabilities. Figure 21 shows a set of typical motor operational curves for starting (accelerating) and for running (see IEEE Std 620™, IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines, for an explanation of the construction of this graph). Generally, with Device 49 protection, the motor protection curve can be placed directly underneath the starting and running damage curves, replicating the exact shape of the damage curve. Thermal overload protection using the Device 49 element generally provides better protection for MV motors than simple overcurrent protection.



Courtesy of Basler Electric Company.

Figure 21—Typical motor curves

Actual motor Thermal Capacity curves or calculations should be available from the motor manufacturer to set the motor protection relay.

NOTE—An example of typical Thermal Capacity calculation from a motor manufacturer is shown in Equation (1) and Equation (2) below:

$$\mathrm{TCU} = (\mathrm{TCU}_{\mathrm{start}} - \mathrm{TCU}_{\mathrm{end}})\, e^{-t/\tau} + \mathrm{TCU}_{\mathrm{end}} \tag{1}$$

$$\mathrm{TCU}_{\mathrm{end}} = \left(\frac{I_{eq}}{S \times I_{tpu}}\right) \times \left(1 - \frac{\text{hot safe stall time}}{\text{cold safe stall time}}\right) \tag{2}$$

Where

TCU is the Thermal Capacity Used, present
$\mathrm{TCU}_{\mathrm{start}}$ is the last calculated TCU value by Equation (1)
$\mathrm{TCU}_{\mathrm{end}}$ is the TCU value computed by Equation (2)
τ is cooling time constant (running or stopped)
I_{eq} is equivalent thermal current
$\mathrm{I}_{\mathrm{tpu}}$ is thermal pickup current
S is load scalar

Equation (1) indicates that the TCU is taken sample by sample, based upon the previous sample over time, t, and shows motor cooling. Note that the exponential function $e^{-t/\tau}$ is a good approximation of the effect (from thermodynamics).

In Equation (2), the final thermal capacity calculation uses the motor manufacturers' hot safe stall time and the cold safe stall time and shows motor running.

Motors on high-inertia loads take a much longer time to accelerate. Without proper protection this long acceleration time could lead to nuisance tripping. In addition, a low-voltage condition at the motor terminals will result in a longer acceleration time because of reduced acceleration torque. Motor torque is related to voltage as follows: The value of motor torque is reduced by the square of the actual motor voltage as a percent of rated motor voltage. If the motor terminal voltage is 80% of rated motor voltage, then the torque the motor produces is reduced by 0.8^2, and the actual motor torque value is 0.64, or 64% of the available torque at 100% rated motor voltage. These situations require careful selection of the type of protection relays and settings. A good practice for these motors is to request motor acceleration curves that are plotted for the cases of 100% and 80% of rated motor-starting voltage. In 8.4.1, other techniques are described for methods of high-inertia start protection. In some cases, protective relays might not adequately solve the problem. A turning gear motor can be applied to start the large-inertia motor.

Motors on high-inertia loads (e.g., reciprocating pumps, reciprocating compressors, and large fans) may require modifications of the Device 49 thermal overload protection curve. Configuration of the overload protection curve should include extended starting times and currents, thus reducing nuisance trips upon starting these devices.

8.3 MV motor overcurrent protection

Figure 22, Figure 23, and Figure 24 illustrate additional techniques for other overcurrent protection approaches for large motors. The accelerating curve is shown differently in each case to demonstrate that no single curve is accepted as a standard. The motor accelerating curve should be provided by the motor or equipment supplier before setting the relays.

In Figure 22, a NEMA Design A or Design B motor curve is shown with protection for starting and running using a Device 51, a time overcurrent relay element with inverse or very inverse characteristics. Within the overcurrent relay is a second element, a Device 50, which operates without delay to protect against a short–circuit;

Device 50 is recommended only for circuit breaker applications and is not recommended for fused starters. Normally three overcurrent elements are used, each element is supplied from a separate CT. Some designers use only two of the three relays for overcurrent protection, and set Device 51 of the third relay relatively low (110% to 120% of the full load current) to alarm on an overcurrent condition. Codes might not permit this practice in some cases, and redundancy is lost during relay testing. In this latter scheme, the two protective phase relays could be set for extreme overcurrent conditions at 125% to 140% of the full load current.

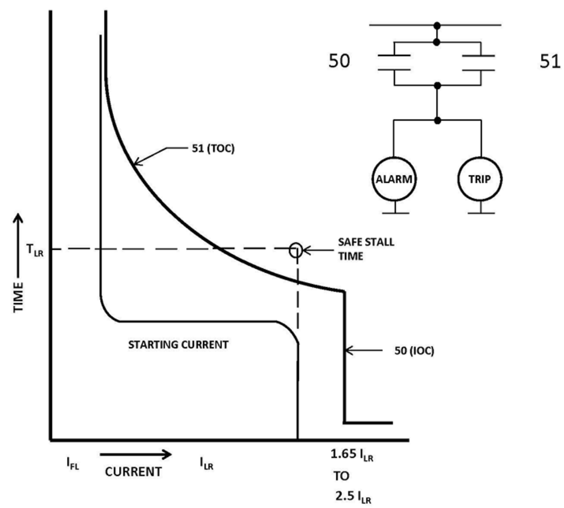


Figure 22—Typical setting of 50/51 overcurrent motor protection

In Figure 23, protection for a high-inertia load allows for the longer accelerating time. A conventional motor reaches rated speed within 10 s to 15 s, a high-inertia load can take 30 s or longer (for example, centrifuges can take as much as 40 min to reach rated speed when starting wye/delta). As a result, little time difference exists between the accelerating current curve and the motor thermal limits. Several approaches are available, as shown in Figure 23 and Figure 24, and an impedance (Device 21) method is shown in Figure 25. In Figure 23, Device 51 has long-time inverse or very-inverse characteristics set above the accelerating current. For starting, a time delay of less than 1 s is needed to permit the Device 50 (HDO) to be set at 1.15 pu of locked rotor current (LRC). This delay reduces false trips caused by asymmetrical starting currents, yet provides short-circuit protection after the time delay. Device 50 is a high dropout (HDO) element that resets rapidly when the starting current drops to a magnitude of 85% to 90% of the set current without delay. (*Definite time delay* is another term to describe this element.) A second Device 50 element is set at approximately two times the LRC to protect against short-circuits during starting.

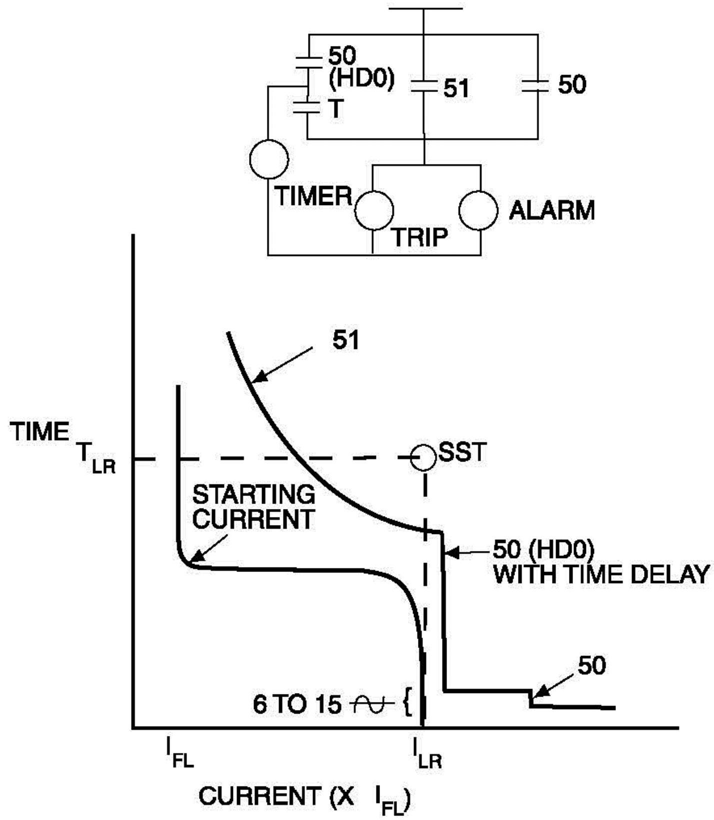


Figure 23—Protection of high-inertia motor

Figure 24 illustrates a second method for protecting a high-inertia motor. This approach also uses two Device 50 elements per phase. The conventional Device 50 is set in the regular way to protect against short-circuits. The second Device 50BT is used in conjunction with a Device 51 overcurrent element to block tripping by the Device 51 for overcurrent conditions less than the Device 50BT setting. This scheme offers an overcurrent alarm, while allowing the motor to continue operating unless the actual overcurrent exceeds a high setting. The use of this scheme is dependent upon the operating philosophy of the facility.

Large motors should be specified with thermistors or RTDs buried in the windings for high-temperature back-up protection. Generally, temperature changes detected with RTD/thermistor thermal overload (Device 49S) are slower to develop than overcurrent increases and the thermal model. Actual faults within the windings would be detected faster by the current differential protection (Device 87) or a sensitive ground fault current (Device 51N) protection schemes.

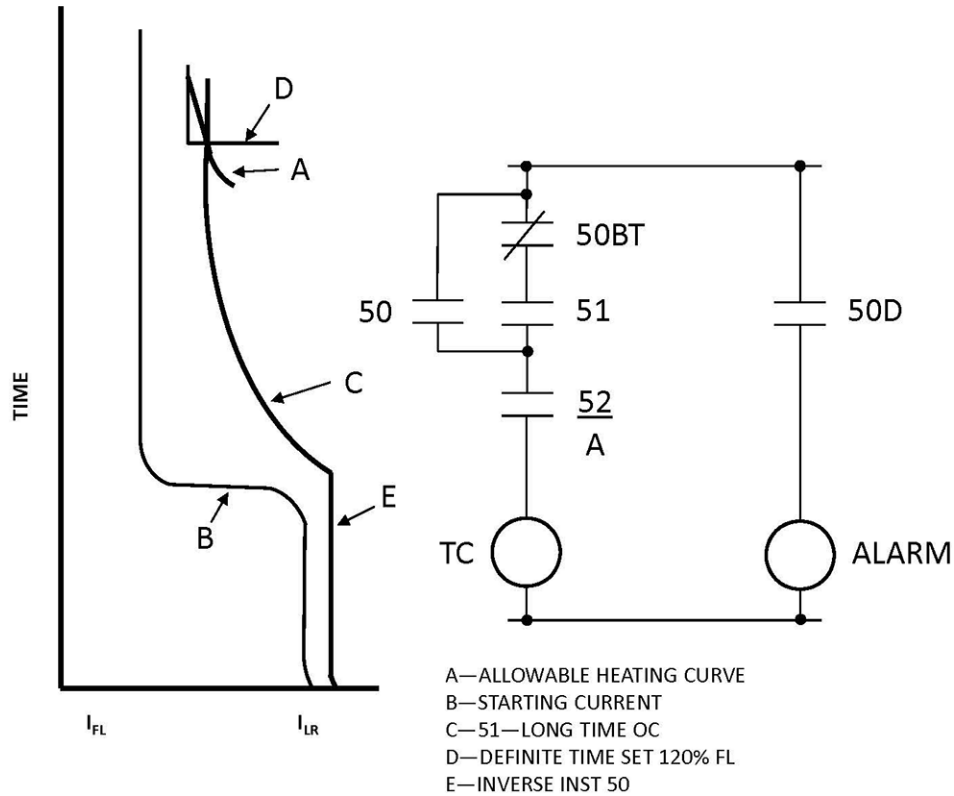


Figure 24—Alternate method of protecting a high-inertia motor

Figure 25 shows a scheme that relies upon the characteristics of an impedance distance element (Device 21) to permit tripping if the high-inertia motor does not accelerate to a certain speed within a fixed period. Upon motor circuit energization, the locked rotor current is primarily inductive, because a blocked motor could be considered a transformer with shorted secondary windings. As the motor accelerates, the current decreases from a subtransient to a transient value, and the power factor and measured impedance increase. Also used with the Device 21 are either an overcurrent relay (Device 51) or an overvoltage relay (Device 59) that operates as a timing device in this case. This scheme guards against a stalled motor. Other schemes exist, such as zero speed devices used with timers (Device 48). Figure 26 illustrates how the locked rotor protection functions below the safe stall time.

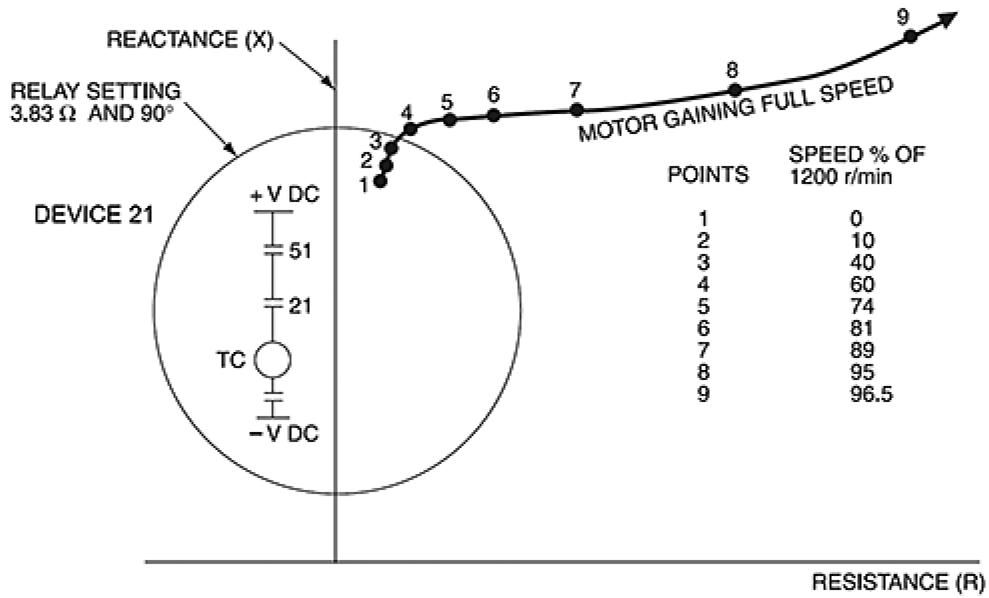


Figure 25—Protection of high-inertia motor using an impedance relay

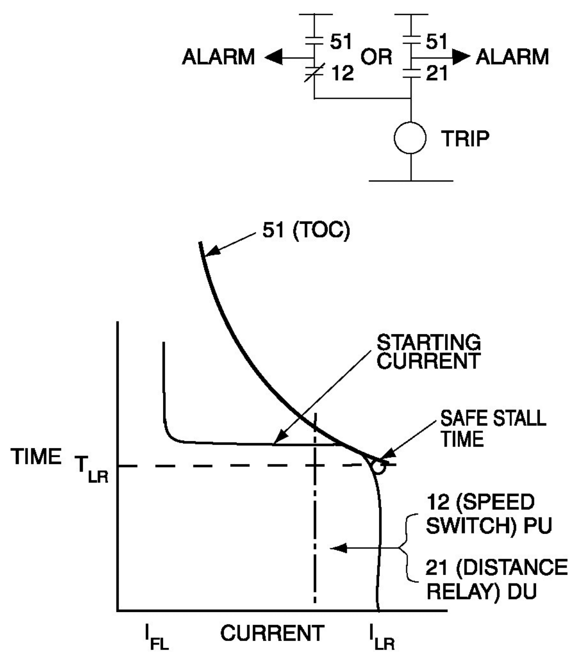


Figure 26—Schematic of locked rotor protection of Figure 25

8.4 Fault protection

8.4.1 Motor current differential element (Device 87M)

8.4.1.1 General

Motor current differential protection measures the current flow into a load and compares it to the current measured on the neutral side of the motor. For normal operation, the current going in and the current going out match and cancel. A current difference is detected as a fault. These schemes can be applied to any motor load, but often are applied only to large or critical motors where damage could be costly or replacement difficult. By detecting faults at a low level, damage can be confined to the windings. The general recommendations for applying differential current protection are as follows:

a) With all motors 750 kW (1000 hp) and larger on ungrounded systems

b) With all motors 750 kW (1000 hp) and larger on grounded systems where the ground fault protection is considered inadequate without differential protection to protect against phase-to-phase faults

c) Motors 1900 kW (2500 hp) and larger

8.4.1.2 Device 87M, Conventional phase differential overcurrent relay

A conventional phase differential relay senses low-level phase faults and removes power quickly before extensive motor damage develops. This scheme uses six identical CTs (one pair for each phase) and three relays (one per phase). The CTs should be sized to carry full load current continuously and to not saturate during an external or internal fault (see Figure 27). The currents from each pair of CTs circulate through the relay-restraining windings under normal (i.e., no-fault) conditions. For a fault in the motor windings or in the cable, the CT secondary currents have different magnitudes and/or polarities, and the differential current from each CT adds to the other and operates the Device 87 to trip the motor circuit breaker. This scheme is employed for both delta connected motors and for wye connected motors. With the wye connected motor, three of the CTs are normally located at the starter (or motor switchgear) and the other three in the three phases at the motor winding neutral. For a delta connected motor, differential protection (Device 50GS) shown in Figure 28 b) should be easier to implement. For conventional differential protection, a large junction box will be required to install CTs and delta winding connection arrangement.

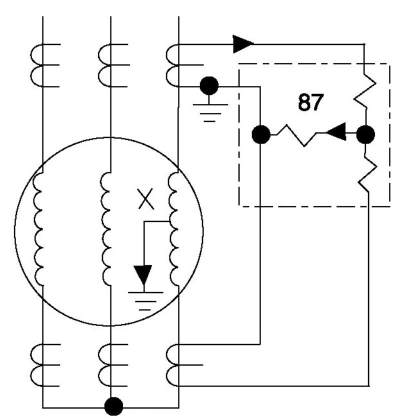
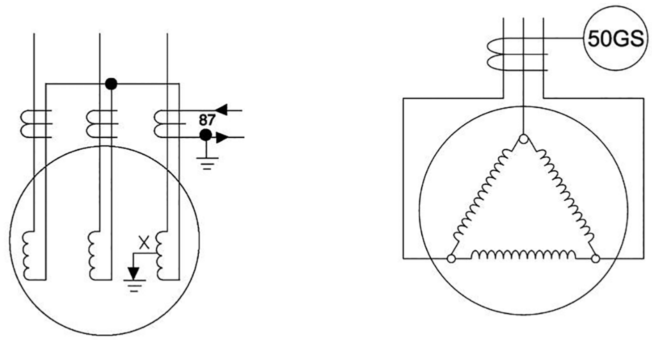


Figure 27—Conventional phase differential protection using three (3) percentage differential relays

8.4.1.3 Devices 87M and 50GS, motor differential protection

For self-balancing differential protection (Device 87M), three window (or toroidal) CTs are normally installed at the motor. One CT per phase is used with the motor line and neutral leads of one phase passed through the CT so that the flux from the two currents normally cancels in the CT. A winding phase-to-phase fault or a phase-to-ground fault results in an output from the CTs of the associated phases. That current operates the associated elements [see Figure 28 a)].



a) Self-balancing differential protection (one element shown)

b) Delta wound motor with 50GS differential protection (unshielded conductors shown)

Figure 28—Motor differential protection

Normally in one relay package, the Device 87 CTs and elements in Figure 28 a) would be the same CTs used for 50GS zero sequence motor differential protection shown in Figure 28 b) and for 50G zero sequence instantaneous ground overcurrent protection (see 8.4.3.2) with the relay set between 0.25 A and 1.0 A pickup. Therefore, the self-balancing differential scheme shown in Figure 28 a) and the 50GS motor protection shown in Figure 28 b) usually has a lower primary pickup in amperes than the conventional differential scheme because the CT ratio is usually greater with the conventional scheme. The differential schemes in Figure 28 a) and b) have a slight advantage over the scheme in Figure 27 in detecting ground faults. For motors installed on grounded systems, this difference is significant because most faults begin as ground faults. The usual objective of motor-fault protection is to remove the fault before the stator iron is damaged significantly.

Application problems have occurred with the schemes in Figure 28 a) and b) when the available fault current is very high and when high speed differential protection signals open the motor starter contactor before the current-limiting fuses clear the fault (thus protecting the starter). Because the starter contactor has such a low fault rating, some engineers have slowed the operation of the relay, by delay or a different relay type, to distinguish between a developing low-level fault and a direct short.

With the CTs located at the motor, these schemes do not detect a fault in the cables supplying power to the motor. Normally, a fault in these cables would be detected by the overcurrent protection. For large motors, coordinating the supply phase-overcurrent protection with the motor thermal overload and overcurrent protection is often a problem. The presence of motor differential protection is considered to make this coordination less essential. In this regard, the current differential is better than the self-balancing differential [Figure 28 a)] because the motor cables are also included in the differential protection zone. Hence coordination between the motor differential and supply phase-overcurrent relays is complete.

As with zero sequence ground fault overcurrent protection, testing the overall CT and relay combinations is important during commissioning. Current in a test conductor should be passed through the window of each CT. Because normally the relays do not carry current, an open circuit in a CT secondary or wiring to a relay can be discovered by overall testing.

8.4.2 Device 87M, split-winding current unbalance

8.4.2.1 Purpose

The purpose of the split-winding current unbalance device is to detect quickly a low-magnitude fault condition. This protection also serves as backup to instantaneous phase-overcurrent and ground fault overcurrent protection. Normally, this protection is applied only to motors having two (or three) winding paths in parallel per phase (see Figure 29). This protection type should not be used on part-winding start applications because the windings are energized at different times during the start sequence. It should be recognized that the CTs are connected to cancel the current for each phase when the system is operating normally.

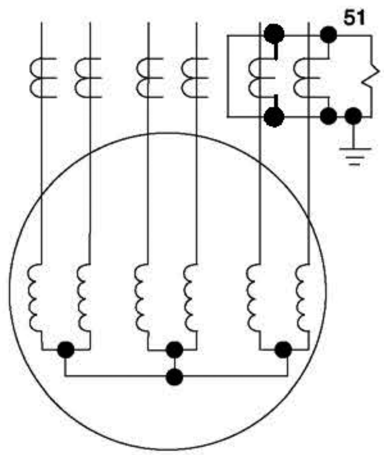


Figure 29—Split-winding motor overcurrent protection used with two windings per phase (one relay shown)

8.4.2.2 Arrangement of CTs and relays

The usual application is with a motor having two or more winding paths in parallel per phase. The six line leads (i.e., two per phase) of the motor are brought out, and one CT is connected in each of the six leads. Choose the primary current rating of the CTs to carry full load current (FLC).

The CTs can be installed at the motor. It might be convenient, however, to use six cables to connect the motor to the starter (or switchgear), and in this case the CTs can be located in the starter.

The currents from each pair of CTs, associated with the same phase, are subtracted, and their difference is fed to a short-time inverse time overcurrent relay. Three of these relays are required (i.e., one per phase), and each is set at 1.0 time dial and between 0.5 A and 2.5 A. The relay should be set above the maximum current unbalance (including CT accuracy) that can occur between the two parallel windings for any motor-loading condition.

8.4.2.3 Evaluation of split-winding current unbalance protection

The following factors should be considered when evaluating split-winding current unbalance protection:

a) Total cost would be somewhat less than conventional current differential and more than self-balancing differential.

b) The primary pickup current for this protection would be about half of the primary pickup current of conventional phase differential because both schemes require the CT primaries to be rated to carry normal load currents. Self-balancing differential would usually have a smaller primary pickup current.

c) This protection has a slight time delay compared to the current differential schemes.

d) When the CTs are located in the motor starter, split-winding protection has the same advantage over self-balancing differential as does current differential, specifically, it detects a fault in the motor cables and might facilitate coordination with the supply feeder overcurrent relays (see 8.4.1.3).

e) A feature of this protection is the ability to sense short-circuited winding turns. The number of turns that are short-circuited before detection occurs depends upon the motor winding arrangement, the relay pickup, and CT ratio. An analysis of the specific motor winding would be required to determine the worth of this feature. Short-circuited turns could cause a ground fault, which could be detected by the self-balancing differential scheme before this split-winding protection would sense the short-circuited turns condition.

f) Often a split differential scheme can be effective where one CT is in one of the parallel paths and the other CT sees the total phase current.

8.4.2.4 Application of split-winding protection

Device 87M split-winding protection is used rarely, but is feasible for important motors that have two or more winding paths in parallel per phase.

8.4.3 Ground fault protection (Devices 50G, 51G, 50N, and 51N)

8.4.3.1 Purpose

The purpose of ground fault protection is to detect ground fault conditions with no intentional delay and to be certain that the unbalance current represents a true ground fault (i.e., not current due to asymmetry in the primary current or current from CT saturation). Upon detecting a ground fault, the protection can trip the motor circuit or only alarm for high resistance grounded systems, depending upon the facility operating practice.

8.4.3.2 Device 50G, instantaneous ground fault protection

Using a zero sequence (or window) CT that has been designed for instantaneous ground fault protection and tested with a specific ground fault relay is recommended (see Figure 30). Refer to Dudor and Padden [B12] for proper termination diagrams for zero sequence CTs with shielded conductors. For MV applications, the power system should be low resistance grounded or hybrid grounded. The Device 50G element should be set to operate for a primary ground fault current in the range of 10 A to 30 A. A time delay should be added when the installation has old-style, gapped (silicon carbide) surge arrester protection on the motors, but is not necessary if metal oxide varistor (MOV) type of arresters are applied.

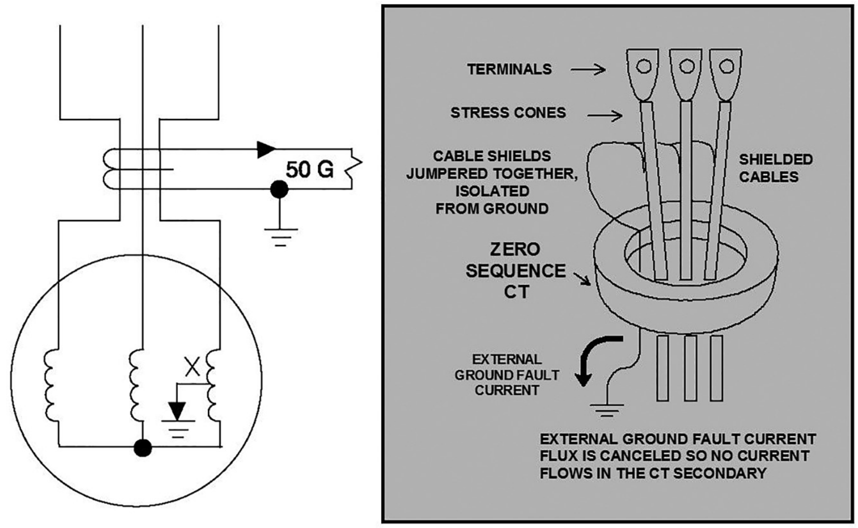


Figure 30—Ground fault overcurrent protection using a zero sequence CT (Dudor and Padden [B12])

8.4.3.3 Device 51G, time overcurrent ground fault protection

Some older installations have gapped-type (silicon carbide) surge protection at the motor terminals, and a surge discharge through this type of arrester could cause an instantaneous relay element to have a false trip. To avoid this event, a Device 51G should be applied, in place of the Device 50G in Figure 30, and set to trip within a few cycles of the fault-sensing pickup. A time delay is not required if MOV type of arresters are applied.

8.4.3.4 Installation of cable for ground fault protection

The following precautions should be observed in applying the relay and zero sequence CT and in installing the cables through the CT:

a) If the cable passes through the CT window and terminates in a pothead on the source side of the CT, the pothead should be mounted on a bracket insulated from ground. Then the pothead should be grounded by passing a ground conductor through the CT window and connecting the ground conductor to the pothead.

b) If metal-covered cable passes through the CT window, the metal covering should be kept on the source side of the CT, insulated from ground. The terminator for the metal covering may be grounded by passing a ground conductor through the CT window and then connecting the ground conductor to the terminator.

c) Cable shields should be grounded by passing a ground conductor through the CT window and then connecting the ground conductor to the shields.

d) The overall CT and ground relay scheme should be tested by passing current in a test conductor through the CT window. Because normally no current exists in the relay, an open circuit in the CT secondary or wiring to the relay can be discovered by this overall test.

8.4.3.5 Device 51N, residually connected CTs and ground fault relay

Using the residual connection from three CTs (i.e., one per phase) to supply the ground fault relay is not ideal because high phase currents (e.g., due from motor starting inrush or phase faults) can cause unequal saturation of the CTs and produce a false residual current measurement. As a result, undesired tripping of the ground

relay can occur. For this reason, a Device 50N is not recommended in the residual connection. A Device 51N installed in the residual connection would be more appropriate for these installations. A 51N function time delay of six cycles is often adequate for electromechanical and microprocessor relays, but it should be recognized that the sensitivity and operating time of the relay may be inadequate. Protection using a zero sequence CT with a 50G relay is preferred.

8.4.3.6 Selection of resistor for low resistance system grounding

The purpose of resistance grounding is to provide current sufficient for protective relays to operate upon detection of a ground fault, but sufficiently small to limit the magnitude and resulting damage to the motor. (In mine distribution systems, the objective is to limit equipment-frame-to-earth voltages for safety reasons.) However, the ground fault current should not be so small that the windings near the neutral end are unprotected. In the past, protection within 5% to 10% of the neutral has often been considered adequate. Selection of the ground resistor should also consider the number of steps in ground fault overcurrent protection coordination (see Love [B36] and Love and Hashemi [B37]). On this basis, the ground resistor chosen for the system neutral grounding limits the ground fault current within the range of 100 A to 1000 A, with 400 A being typical (IEC 60288-149:2013 [B20] and IEEE Std 142™ [B24]). This difference emphasizes the need to coordinate the protection of a system. Usually, a 10 s time rating is chosen for the resistor.

To avoid excessive transient overvoltages, the resistor should be chosen so that the following zero sequence impedance ratio is achieved:

R_0/X_0 should be equal to or greater than 2.

A more detailed discussion of the selection of the resistor can be found in Chapter 8 of IEEE Std 242-2001 and IEEE Std 142-2007 (*IEEE Green Book*™) [B24].

8.5 Monitors

8.5.1 Introduction

In addition to protection against failures caused by electrical abnormalities, advances in instrumentation and techniques have enabled protective methods that monitor machinery characteristics and, as a result, can detect trends of equipment failures during the incipient stage. This development has manifested monitors, sensors, and detectors that use inputs not related directly to measured electrical quantities of voltage and current.

8.5.2 Stator winding overtemperature (Device 49S)

8.5.2.1 General

The purpose of stator winding overtemperature protection is to detect excessive stator winding temperatures prior to motor damage. Often, this protection is arranged just to alarm on motors operated with competent supervision. Sometimes two temperature settings are used, the lower setting for alarm, the higher setting to trip. The trip setting depends on the type of winding insulation and on the user's operating requirements. Stator overtemperature trip is usually set 5 °C to 10 °C below the insulation class maximum temperature rating. Motor manufacturers may provide recommended alarm and trip settings; and for NEMA motors a maximum allowed temperature setting might be provided.

8.5.2.2 Device 49S, RTDs

Six RTDs (two per phase) should be specified in motors rated 375 kW (500 hp) and greater. These devices are installed in the winding slots when the motor is being wound. The six RTDs are spaced around the circumference of the motor core to monitor all phases. The most commonly used type is three-lead 100 Ω platinum. Other elements and lead configurations are available. For example, a four-lead RTD is used for applications that require higher accuracy. The RTD device resistance increases with temperature, and a Wheatstone bridge or

similar circuitry is used to provide temperature indication and output operation. The value of the temperature trip depends on the type of winding insulation used and the operating requirements of the user. The RTD type and the monitor input type must match.

For safety, RTDs should be grounded, and that ground in turn places a ground on the control module. Therefore, the control module should not be operated directly from a switchgear dc battery because these dc control schemes should normally operate ungrounded to achieve better reliability. However, loss of ac control voltage caused by an opened fuse could remove protection, unless the null point is near the trip setting at which time it could cause tripping.

An open RTD or an open RTD circuit appears as an infinite resistance and causes a false trip because this corresponds to a very high temperature. Some motor protection relays use RTD voting to reduce the threat of a false temperature reading (and subsequent false alarms and false tripping). To indicate an excess-temperature condition, the relay must receive high-temperature indications from multiple RTDs (the number of RTD votes is configurable). In this way damaged and open-circuit RTD inputs are ignored.

The following arrangements of RTDs are used frequently:

a) Monitor all six leads continuously with alarm points and time-delayed higher trip points using one monitor or a programmable logic controller.
b) Monitor six leads with alarm points and use a manual trip.
c) Configure alarm points and trip points for selected sectors of the motor. Use a selector switch and combination indicator and alarm elements. (Precaution: An open circuit in the switch contact will cause a false trip. Bridging contacts are required.)
d) Use a selector switch and an indicator only.
e) Use one, two, or three (i.e., one per phase) alarm relays; and use one, two, or three (i.e., one per phase) trip relays set at a higher temperature.

The arrangement and monitoring of the RTDs should identify damaged RTDs. A damaged RTD or RTD connection circuit will typically exhibit either an open-circuit or a short-circuit. The protection system should be able to identify these conditions and annunciate an appropriate alarm. An open RTD or an open RTD circuit will appear as an infinite resistance to the protection system and, if not identified as an open-circuit by the protection system, will cause a false trip because the measured infinite resistance will be identified as a very high temperature. A shorted RTD or a shorted RTD circuit will appear as a resistance lower than the range for a given RTD selection. If not identified as a shorted RTD or a short-circuit by the protection system, a very low temperature will be recorded and actual RTD temperature will not be valid.

When there are two or more RTDs per phase, RTD voting provides an extra level of thermal feedback reliability, for motor thermal protection, in the event of individual RTD or wiring malfunctions. If enabled, a second (or more) healthy RTD must indicate a temperature in excess of the trip-temperature set point, for any enabled RTD channels, before a trip command will be issued by the protection system. This feature provides for uninterrupted operation when a single damaged or open-circuit RTD input is detected. An alarm protection setting should be configured to identify the degradation of any given RTD input.

RTD voting typically applies only to RTD channels assigned for winding temperature monitoring.

If RTD voting protection is not enabled, any one winding RTD temperature input, in excess of its trip temperature setting, will initiate a motor trip if the control scheme is configured to do so.

8.5.2.3 Device 49S, thermocouples

Thermocouples are used to indicate temperatures for alarm and trip functions, in a similar manner to RTDs. However, an open circuit in the thermocouple leads does not cause a trip because the output appears as a low-temperature condition. Where higher accuracy is required, use of a Class 1 thermocouple is advised. Use suitable thermocouple extension cable when locating the thermocouple more than 0.5 m from the transducer.

For safety, similar to the RTDs, the thermocouple must have a grounded junction. Usually, thermocouple grounding is on the sheath at the terminal box. Thermocouple outputs are compatible with conventional temperature-monitoring and data-logging schemes, and some relays have (4 mA to 20 mA and 0 V to 10 V) analog inputs for inputting thermocouple data via the proper interface.

Thermocouple cable must have a temperature rating for the specific application. Refer to ASTM E230 [B5] and ASTM E585 [B6].

8.5.2.4 Device 49S, thermistors

Thermistors are used as an input to protective devices with alarm or trip functions, or both. These devices may be used to provide temperature indication. Thermistors may also be combined with thermocouples, which provide indication, while the thermistor is an input to a relatively inexpensive relay. See 7.4.3 for further details. The controller specifications must align with the thermistors.

8.5.2.5 Device 49S, thermostats and temperature bulbs

Thermostats and temperature bulbs are used on some motors. For instance, thermostats are bimetallic elements and are used on random-wound motors (< 1000 V, not MV motors) to detect failure to start. These are embedded in the end windings and provide a contact opening to trip the motor. Bulb temperature devices are used to provide measurement and trip contacts for bearing oil temperature in oil-lubricated bearings. See 7.4.2 for further details.

8.5.2.6 Application of stator winding temperature protection

Stator winding temperature protection is commonly specified for motors rated 185 kW (250 hp) and more. RTDs are commonly specified for motors rated 375 kW (500 hp) and more. In the following situations, applying stator winding temperature protection should be considered:

a) Motors in high ambient temperatures or at high altitudes
b) Motors with ventilation systems that tend to become dirty and lose cooling effectiveness
c) Motors subject to periodic overloading caused by load characteristics
d) Motors likely to be subjected to continuous overloading (within their service factor range) to increase production
e) Motors used in critical continuity of service applications
f) Motors supplied from ASDs
g) Motors in hazardous (Classified) locations

8.5.3 Rotor overtemperature (Device 49R)

8.5.3.1 Rotors in synchronous motors

Rotor winding overtemperature protection, Device 49R, is available for synchronous motors, although normally, this protection is not used. One well-known approach is to use a Kelvin bridge-chart recorder with con-

tacts adjustable to the needed temperature settings. The Kelvin bridge uses field voltage and field current (from a shunt) as inputs and measures the field resistance to determine the field winding temperature.

8.5.3.2 Wound-rotor induction motor-starting resistors

Some form of temperature protection should be applied for wound-rotor induction motor-starting resistors on motors having severe starting requirements, such as long acceleration intervals or frequent starting. RTDs and other types of temperature sensors can be used.

8.5.4 Mechanical and other protection

8.5.4.1 General

Protection that detects currents that can cause bearing damage should be considered for motors. Recent research in vibration rotor-bar heating has discovered that these conditions exhibit discernible signatures (usually in the frequency domain). Specialized equipment detects this effect, and is used on large and critical-application motors (Gritli, et al. [B17] and Teotrakool, Devany, and Eren [B62]).

8.5.4.2 Motor bearing and lubricating systems

Various types of temperature sensors are used on bearings to detect overheating, such as RTDs, thermocouples, thermistors, thermostats, and temperature bulbs. Excessive bearing temperature might not be detected in time to prevent bearing damage. More serious mechanical damage to the rotor and stator can be reduced by tripping the motor before complete bearing failure. Thus, for better effectiveness, the following steps are recommended:

a) Use a fast-responding temperature sensor.

b) For rolling element bearings, locate the temperature sensor in contact with the bearing metal where it is close to the source of overheating (if known).

c) For fluid film bearings, internal bearing temperature sensors are recommended. Typically an RTD, thermocouple, or other temperature sensor is imbedded directly in the metal of the bearing close to the Babbitt backing. Refer to API 670 Section 6.1.8 for internal bearing temperature monitoring.

d) Use the temperature sensor for tripping instead of alarm only; for some installations, use both alarm and trip sensors, the former having a lower temperature setting.

e) For critical motors, consider monitoring more than one temperature sensor per bearing to avoid nuisance tripping and to provide temperature sensor failure backup.

f) Provide alarm and trip devices on bearing lubricating systems to monitor the following:

    1) Lubricating oil temperature, preferably from each bearing

    NOTE—Lubricating oil temperature monitoring has a slower response time than imbedded bearing temperature measurement and should only be used as a secondary measurement to corroborate machinery problems when timeliness is not a concern.

    2) Bearing cooling-water temperature, both temperature in and out

    3) Bearing lubricating-oil flow and cooling-water flow

    4) Lubricating-oil pressure (typically large motors) and cooling-water pressure

    5) Differential pressure across filter

In lieu of the flow-monitoring recommended in item f) 3), often a suitable arrangement of pressure switches is used. However, flow monitoring is strongly recommended for important or high-speed machines.

Temperature sensors generally cannot detect impending failure of ball bearings and roller bearings in time to be effective. Vibration monitors and detectors should be considered (see 8.5.5).

In IEEE Std 1349-2011, "Some motor bearing systems are designed by the motor manufacturer to be insulated to protect the bearing from developing shaft currents across the oil film. In some applications, one bearing is insulated. In some other applications, both bearings are insulated and a grounding jumper is installed on one bearing. Voltage induced on a motor shaft can result in a circulating current with a magnitude limited by the bearing impedance. This bearing impedance acts as a capacitor with the oil film acting as the dielectric in a capacitor that is charged by the shaft voltage. When the shaft voltage across the oil-film capacitor reaches its dielectric-breakdown voltage, a discharge occurs which can cause pitting in the bearing. Experience shows that the amount of energy discharged across the oil film does not produce a spark that could cause ignition. It is recommended that the insulation and grounding should be discussed with the motor manufacturer and maintained to reduce damage to the bearings (see Costello [B11]). For ASD applications, refer to IEEE Std 1349™-2011 for CMV calculations showing the amount of energy discharge across the oil film."

8.5.4.3 Ventilation and cooling systems

Alarm and trip devices should be considered, as follows:

a) In motor ventilation systems
   1) To detect high differential pressure drop across air filters
   2) To detect loss of air flow from external blowers (In lieu of air-flow monitoring, a suitable arrangement of pressure switches is often used; however, flow monitoring is preferred.)
b) With water-cooled motors, to monitor water temperature, flow, and pressure
c) With inert-gas-cooled motors, to sense pressure and temperature
d) For motors in hazardous areas, to detect flammable gasses and vapors

For purged and pressurized enclosures also see NFPA 496-2008 [B46].

8.5.4.4 Liquid detectors

On large machines, sometimes liquid detectors are provided to detect liquid (usually water) inside the stator frame, e.g., because of a leak in the air cooler of a totally enclosed water- and air-cooled motor.

8.5.4.5 Fire detection and protection

For fire detection and protection, the following items should be considered:

a) Installation of suitable smoke and flame detectors to alert operators to use suitable portable fire extinguishers.
b) Installation of suitable smoke and flame detectors and an automatic system to apply carbon dioxide or other suppressant into the motor. Some old, large motors have internal piping to apply water for fire extinguishing. Possible false release of the water is a serious disadvantage.
c) Use of synthetic lubricating oil that does not burn, particularly for drives having large lubricating systems and reservoirs and for systems in hazardous atmospheres. Lubricating systems, which meet the hazardous-area classification, of gas compressors or hydrocarbon pumps should be kept separate from the motor to preclude combustibles and flammables from entering the motor through the oil system.

   NOTE 1—"Common lubricating oil systems should be avoided because a pump or compressor process seal failure can allow flammable material to enter the lubricating oil system. This circulated lubricating oil containing flammable materials then enters the motor's bearing housing. Flammable material can pass into the motor en-

closure through the seals between the motor's bearing housing and the motor enclosure. Over time an explosive accumulation of flammable material can build up in the motor enclosure. This explosive material buildup could then be ignited by an internal ignition source. Although starting of a motor is not considered a normal operating condition, if the flammable material accumulated during a running condition, it might also be ignited during a future start. Refer to Annex J, Table J.1 items 3, 4, 6, 7 and 8 [in IEEE Std 1349-2011]. An alternative to total separation of the two systems is to install degassing equipment to ensure that the lubricating oil is totally gas free at all times." (See IEEE Std 1349™-2011.) Another alternative is to use pedestal bearings for the motor; by design, they are located outside of the motor enclosure.

NOTE 2—For lubricating oil systems, reference API Std 614, Lubrication, Shaft-sealing and Oil-control Systems and Auxiliaries, 5th Edition (ISO 10438:2008, Modified), Includes Errata (2008) [B4].

8.5.4.6 Partial discharge (PD) detectors

There are a variety of PD detection devices and monitors. Refer to Annex C for a more detailed discussion. These detectors show a pattern of frequencies that are normal for a motor. Abnormal patterns of corona can indicate insulation degradation. PD detectors should be considered for motors 4000 V and above, particularly for motors in critical service.

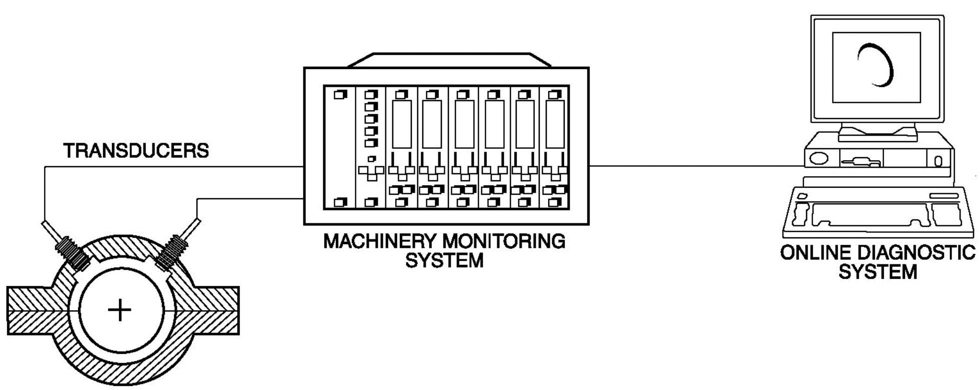
8.5.4.7 Monitoring motor insulation online

The capacitance (C) and dissipation factor (DF) measurement of motor ground-wall insulation is one of the standard tests to determine the insulation health. This online monitoring is discussed further in Annex C.

8.5.5 Vibration monitors, sensors, and machinery protection systems

8.5.5.1 Purpose of vibration monitoring

Vibration monitoring is an important startup function and an effective tool during operation of the process. There are several induction motor problems that result in high vibration at running or operating speed: broken rotor bars and/or shorting rings, loose rotor bars, mass unbalance coupling lockup, and eccentric bearing journal (Al-Ali and Dabbousi [B1]). Vibration monitoring and protection increase safety and reliability and can reduce costs over the life of the plant. The three components of a vibration-monitoring system are transducers, monitors, and machine diagnostic equipment, although some installations might not have permanent monitors and diagnostic systems (see Figure 31).



Courtesy of GE Bentley-Nevada.

Figure 31—Vibration-monitoring system

8.5.5.2 Transducers

Transducers are a critical part of a vibration monitoring system. Accurate machinery diagnostics depend upon reliable transducer signals. Two orthogonal, or XY, transducers should be installed at or near each bearing; and a phase reference probe, such as a once-per-turn event probe, should be installed on each shaft. This configuration provides diagnostic equipment with the information necessary to indicate accurately the vibratory motion. Transducers should be of rugged construction to withstand the motor's environment. In general, if rotor-related malfunctions are anticipated (e.g., unbalance, misalignment, rubbing), vibration transducers that observe the rotor are preferred. If housing-related malfunctions are anticipated (e.g., piping strains, structural resonances), transducers mounted on the machine housing are preferred.

As discussed in API 541, for vertical motors axial position probes are normally applied to monitor thrust loading and hydrodynamic thrust bearing condition. Occasionally, axial position probes are used to monitor a rotor's axial vibration. For horizontal motors, axial probes should not generally be applied because no thrust bearing is present and because axial probes used as vibration sensors will not generally accommodate the rotor's relatively large amount of axial motion. For high-speed motors with hydrodynamic radial bearings, noncontacting vibration systems are generally used to detect vibration. For antifriction bearings that have high transmissibility of shaft-to-bearing force, accelerometer systems are generally used to detect vibration. For motors with 14 or more poles, vibration probes are not normally used.

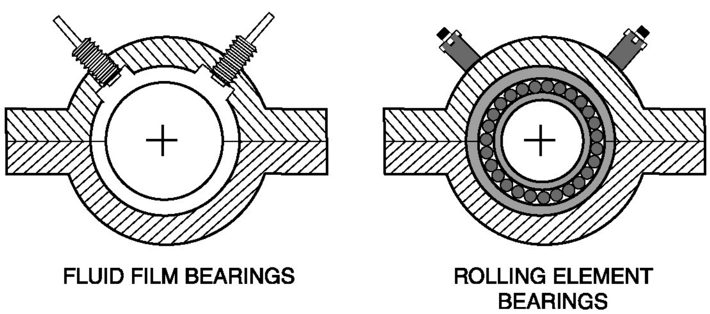
8.5.5.3 Proximity transducers

8.5.5.3.1 General

On motors with fluid-film bearings, such as sleeve bearings, noncontacting proximity transducers provide the best data and are preferred. Figure 32 shows a typical proximity transducer system and Figure 33 shows the cross-section installation of proximity transducers and case mounted transducers. Often on these motors, much of the rotor motion is not transmitted to the housing, therefore transducers mounted on the housing such as accelerometers and velocity probes provide limited usefulness. Noncontacting proximity transducers indicate accurately the rotor displacement relative to the housing. These transducers have a broad frequency response, from dc (i.e., 0 Hz) at the low end up to 10 kHz. However, useful application at high frequencies is limited because little measurable displacement occurs at high frequencies. Proximity transducers can measure slow-roll and the shaft's average position within the bearing. For motors with rolling-element bearings, consider an accelerometer or velocity sensor. See Figure 35 for a vibration limit curve example.

Courtesy of GE Bentley-Nevada.

Figure 32—Typical proximity transducer system: proximitor, cable, and probe



Courtesy of GE Bentley-Nevada.

Figure 33—Typical proximity transducer installations

8.5.5.3.2 Velocity transducers

Velocity transducers may be used on motors with rolling-element bearings if virtually all of the shaft motion is faithfully transmitted to the bearing housing. Velocity transducers are seismic devices (accelerometer with internal integration to velocity) that measure motion relative to free space, these transducers are useful for overall vibration measurement, and provide good frequency response in the mid-frequency range (4.5 Hz to 1 kHz). Pay close attention to the frequency response of the prospective sensor to be sure the sensor has a good frequency response in the frequencies of interest such as: rolling element bearing ball-pass, outer race, etc. This transducer is self-generating; no power source is required. Traditional velocity transducers are mechanical devices that suffer from a limited life span. Some modern velocity transducers use a piezoelectric sensing

element, these transducers do not have a limited life span, and are thus preferred. See Figure 36 for a vibration limit curve example.

8.5.5.3.3 Accelerometers

Accelerometers are generally used on motors with rolling-element bearings if virtually all of the shaft motion is transmitted to the bearing housing. Accelerometers are useful for overall vibration measurements and have a broad frequency response. It is important to evaluate the frequency response of the prospective sensor to be sure that the sensor has a good frequency response in the frequencies of interest such as: rolling element bearing ball-pass, outer race, etc. These devices are particularly useful for high-frequency measurements. An accelerometer is virtually the only viable transducer at high frequencies (usually above 5 kHz). Motor vibration acceleration increases with frequency. Therefore, the acceleration unit of measurement is preferred. However, at low frequencies, accelerometer usefulness is limited. Accelerometers are sensitive to the method of attachment and the quality of the mounting surface.

8.5.5.4 Monitors

8.5.5.4.1 Monitors process and display transducer signals

Monitors should detect malfunctions in the transducer system and the transducer power supply. These devices should provide two levels of alarm and protect against false alarms. Monitors should be constructed so that both the unprocessed and processed information is available to online and portable diagnostic equipment. Monitors designed to work with accelerometers or velocity transducers should be able to integrate the signal. Modern machinery protection systems feature extremely reliable relays that also incorporate advanced relay logic and time delay capabilities. See Figure 34 for sample monitoring system panels.

Courtesy of GE Bentley-Nevada.

Figure 34—Vibration monitoring system panels

8.5.5.4.2 Continuous monitors

Motors that are critical to a process should be instrumented with continuous monitors, in which each monitor channel is dedicated to a single transducer. These monitors have the fastest response time and provide the highest level of motor protection.

8.5.5.4.3 Periodic monitors

General purpose motors can be instrumented with periodic monitors, in which each monitor channel is time-shared among many transducers. Consequently, the response time is slower than the continuous monitor.

8.5.5.4.4 Portable monitors

Portable monitors are used widely, primarily when a permanent monitoring system has not been justified. Often portable monitors are used with infrared scanners to determine whether bearings are overheating. The

results are suitable for trending in a condition-based maintenance program. Other types of portable monitors include ultrasonic probes as a part of a maintenance program.

8.5.5.5 Diagnostic systems

8.5.5.5.1 Purpose of diagnostic systems

A diagnostic system is essential to effective machinery management. Using computing technology, the system processes the data provided by the transducers and monitors into information that can be used to make decisions regarding motor operation. A diagnostic system should be capable of simultaneously processing the data from two orthogonal transducers along with a once-per-turn reference (phase) probe. It should display data in several plot formats, including orbit, time base, Bode, polar, shaft centerline, trend, spectrum, and full spectrum. It should reduce operator involvement in motor configuration and data acquisition. It should display alarms for each monitored channel, trend data over time, and archive data to a storage medium (e.g., computer disk). It should integrate with computer networks and control systems.

8.5.5.5.2 Continuous online diagnostic systems

Motors that are critical to a process should be managed by a continuous online diagnostic system. Each channel in a continuous online diagnostic system is dedicated to the data from a single transducer and monitor channel. The diagnostic system processes machinery information online, where the data are sampled continuously and are available to the host computer. A diagnostic system that processes steady state information during normal operation is a minimum requirement; the diagnostic system should be capable of processing data both during startups and shutdowns. The system should be capable of displaying information in real time. The continuous online diagnostic system should be evaluated for protection level, motor and production costs, time to replace motors, etc. to determine its economic feasibility.

8.5.5.5.3 Periodic online diagnostic systems

General purpose motors can be managed by an online periodic diagnostic system. Each channel in a periodic system can be shared among many transducers. The data are sampled periodically and are available continuously to the host computer.

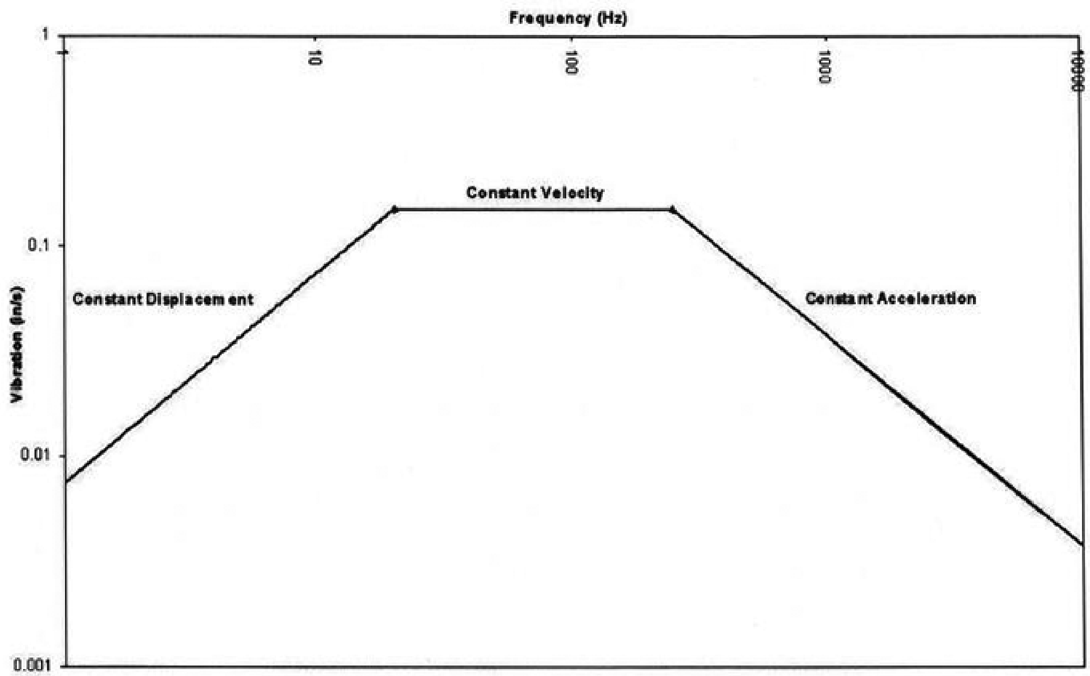
8.5.5.5.4 Vibration limits

The vibration limits for motor shafts and bearing housings depend mainly on the operating speed. For NEMA Frame sized motors, examples of vibration limits (unfiltered measurement) are shown in Table 7 for motor housing and Figure 35 for resiliently mounted motors from NEMA MG-1-2011, Part 7.

Table 7—Unfiltered housing vibration limits per NEMA MG-1-2011, Part 7

NEMA frame size			140 ≤ NEMA frame ≤ 210			210 < NEMA frame ≤ 440			NEMA frame > 440		
Vibration grade	Mounting		Displacement mils pk-pk	Velocity in/s g pk	Accelera-tion g pk	Displacement mils pk-pk	Velocity in/s pk	Accelera-tion pk	Displacement mils pk-pk	Velocity in/s pk	Accelera-tion g pk
A	resilient		2.4	0.15	0.61	2.4	0.15	0.61	2.4	0.15	0.61
	rigid		1.9	0.12	0.49	1.9	0.12	0.49	1.9	0.12	0.49
B	resilient		1.0	0.06	0.24	1.3	0.08	0.33	1.6	0.10	0.41
	rigid	2, 4, 6 pole	N/A			1.3	0.08	0.33	1.6	0.10	0.41
		8+ pole	N/A			1.0	0.06	0.24	1.3	0.08	0.33
NOTE—Rigid mounting is not considered acceptable for NEMA frame sizes 210 and smaller.											

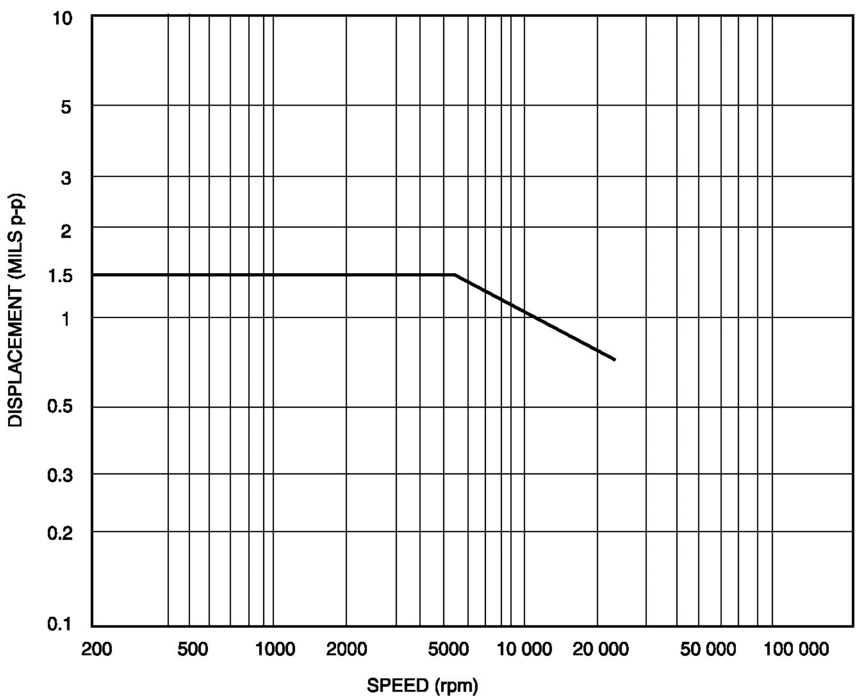
Reprinted by permission of the National Electrical Manufacturers Association from NEMA MG-1-2011, Table 7-1.



Reprinted by permission of the National Electrical Manufacturers Association from NEMA MG-1-2011, Figure 7 through Figure 6.

Figure 35—Machine vibration limits (Resiliently Mounted) per NEMA MG-1-2011, Part 7

API Std 541–1995 recommends limits for shaft and bearing vibrations, using noncontact vibration probes on hydrodynamic bearing motors operating at speeds equal to or greater than 1200 r/min. Examples of these limits are shown in Figure 36 and Figure 37 from API Std 541–1995. Updated vibration limits for special purpose form wound induction motors (500 hp and larger) are described in API Std 541–2014, 5th Edition, Figure 3 and Figure 5, and for large synchronous motors are described in API Std 546, 3rd Edition. Vibration limits are also provided in API Std 547, 1st Edition, and IEEE Std 841™ for form-wound and totally enclosed fan-cooled (TEFC) motors, respectively.



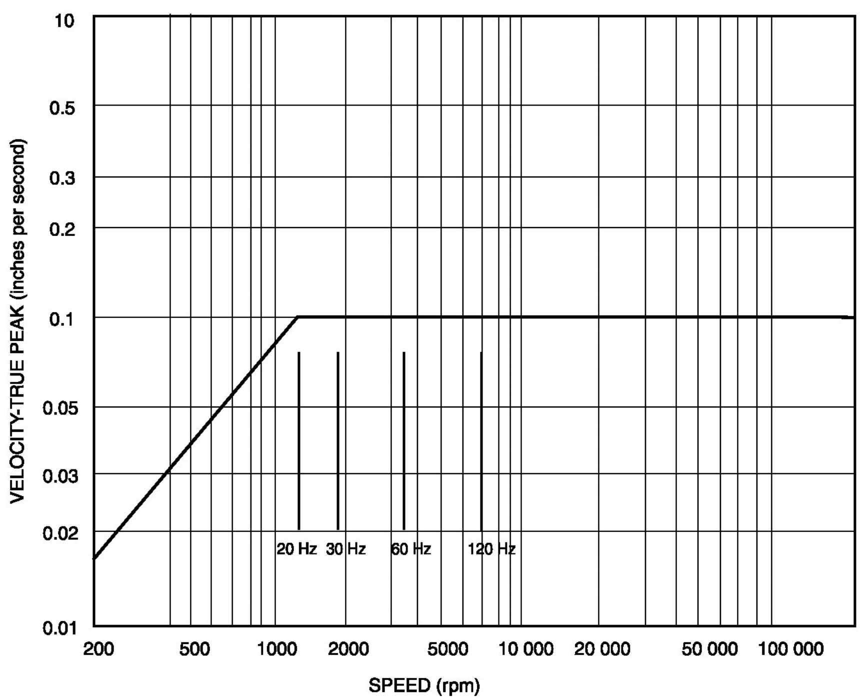
Reprinted with permission from Section 3.8 of API 541-1995 (IEEE Std 242-2001, *IEEE Buff Book*™).

NOTE 1—Vibration displacement at any frequency below running-speed frequency shall not exceed 0.1 mil or 20% of the measured unfiltered vibration displacement, whichever is greater.

NOTE 2—Vibration displacement at any filtered frequency above running-speed frequency shall not exceed 0.5 mil peak to peak.

NOTE 3—Vibration displacement filtered at running-speed frequency shall not exceed 80% of the unfiltered limit (runout compensated).

Figure 36—Shaft vibration limits (relative to bearing housing using non-contact vibration probes): for all hydrodynamic sleeve-bearing motors; with the motor securely fastened to a massive foundation



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NOTE 1—For unfiltered vibration limits, use motor synchronous or maximum rotational speed in revolutions per minute.

NOTE 2—For filtered limits, use vibration frequency in hertz.

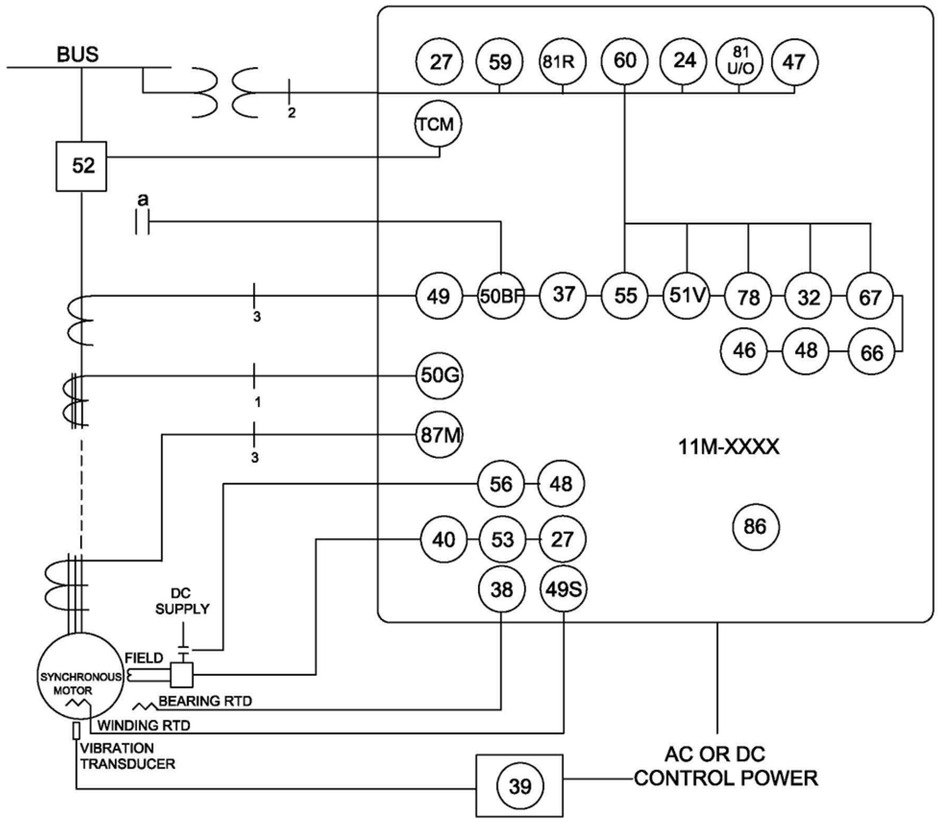
NOTE 3—Limits are for sleeve and antifriction bearing motors.

Figure 37—Bearing housing vibration limits: for sleeve and antifriction bearing motors; with the motor securely fastened to a massive foundation

8.6 Synchronous motor protection

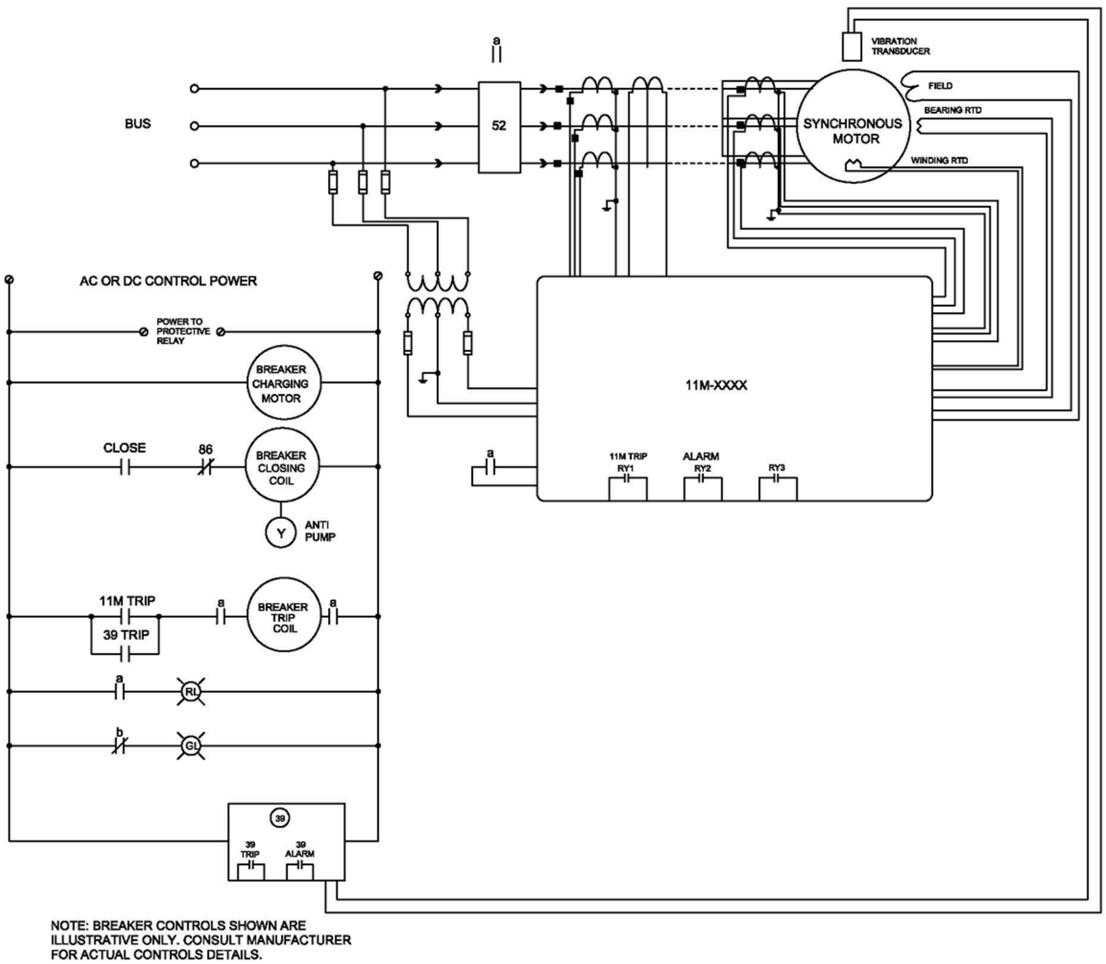
8.6.1 General

Refer to Figure 38 and Figure 39 for typical 1-line and 3-line diagrams of MV synchronous motor protection using a breaker. Synchronous motors have excitation provided by dc power applied to the machine rotor. Therefore, additional protection functions are required. These functions are listed in Table B.2. The critical service protection functions from Table 6 are illustrated using a multifunction motor protection relay, Device 11M. Device 11M signals to trip the breaker for various conditions including short-circuit protection.



Courtesy of C&I Engineering.

Figure 38—MV synchronous motor protection 1-line diagram, Device 11M, critical service protection functions, with breaker



Courtesy of C&I Engineering.

Figure 39—MV synchronous motor protection 3-line diagram, Device 11M, critical service protection functions, with breaker

8.6.2 Amortisseur (damper) winding protection

When a synchronous motor with an amortisseur winding is started across-the-line, high currents are induced in its rotor amortisseur winding. If the motor accelerating time exceeds specifications, the amortisseur winding can overheat and be damaged.

Several different electromechanical and electronic protection schemes are available. None of these schemes senses directly amortisseur-winding temperature. Instead, these schemes simulate the temperature by evaluating two or more of the following quantities:

a) Magnitude of induced field current that flows through a field discharge resistor. This value is a measure of the relative magnitude of induced amortisseur-winding current.

b) Frequency of induced field current that flows through the discharge resistor. This value is a measure of rotor speed and provides an indicator of the increase in amortisseur-winding thermal capability resulting from the ventilation effect and the decrease of induced current.

c) Time interval after starting.

8.6.3 Field-current failure protection

Field current might drop to zero, or to a low value, when a synchronous motor is operating. Some of the reasons for this effect are as follows:

- Tripping of the remote exciter, either motor-generator set or electronic. (Controls for these should be arranged so that the remote exciter will not drop out on an ac voltage dip.)
- Burnout of the field contactor coil. (The control should be arranged so that the field contactor does not drop out on an ac voltage dip.)
- Accidental tripping of the field. (Field-circuit overcurrent protection is usually omitted from field breakers and contactors to avoid unnecessary tripping.) The field circuit is usually ungrounded and should have ground detection lights or a relay element applied to detect the first ground fault before a short-circuit occurs (see 8.6).
- High resistance contact or an open circuit between slip ring and brushes from excessive wear and misalignment.
- Failure of the diode bridge on rotating diodes on a brushless exciter (detected by pullout relays or a power-factor Device 55 element).
- Undervoltage of supply.

Reduced field-current conditions should be detected for the following reasons:

- Overloaded motors pull out of step and stall.
- Lightly loaded motors are not capable of accepting load when required.
- Normally loaded motors can pull out of step on an ac voltage sag; though usually, the motor rides through sags.
- The excitation drawn from the power system by large motors may cause a serious system voltage drop and endanger service continuity to other motors.

A common approach to field-current failure protection is to use an instantaneous dc undercurrent relay to monitor field current. This application should be analyzed to verify that no transient conditions would reduce the field current and cause unnecessary tripping of this instantaneous relay. To avoid nuisance tripping, a time delay of one or more seconds can be used. It is recommended to trip the motor on field-current failure. Another approach is to use a constant-current source to monitor field resistance; a sudden lower reading indicates a ground fault. Some protection schemes inject a square wave into the field circuit, and monitor the returned signal for rounded edges that indicate a change in field-coil conditions.

Field-current failure protection is also obtained by the generator loss-of-excitation relay that operates from the VTs and CTs that monitor motor stator voltages and current (VAR-import Device 40 and power-factor Device 55 protection). This approach has been applied on some large motors (i.e., 3000 kW [4000 hp] and above). This relay can also provide pullout protection as discussed in 8.6.5.

8.6.4 Excitation voltage availability

Device 56 is a relay that has automatic control of field excitation to an ac motor (related to permissive control function). This device is a frequency relay, but others apply a simple voltage relay as a permissive start to confirm that voltage is available from the remote exciter. This approach avoids starting and then having to trip

because excitation was not available. Loss of excitation voltage is not normally used as a trip; field-current failure protection is used for this function.

8.6.5 Pullout protection (Devices 55, 40, and 78)

Pulling out of step is detected usually by one of the following relay schemes:

a) A power factor relay (Device 55) responding to motor stator voltage and current with inputs from the VTs and CTs. Refer to item b) for the discussion on the need to delay actuation of the pullout relay until the motor has a chance to pull into synchronism during a calculated period.

b) An instantaneous relay connected in the secondary of a transformer with the primary carrying the dc field current. The normal dc field current is not transformed. When the motor pulls out of step, alternating currents are induced in the field circuit and transformed to operate the pullout relay. This relay, while inexpensive, is sometimes subject to false tripping on ac transients accompanying external system fault conditions and also ac transients caused by pulsations in reciprocating compressor drive applications. Device 95 has sometimes been used to designate this relay.

c) The generator loss-of-excitation relay (Device 40).

d) Out-of-step protection (Device 78).

8.6.6 Protection against excessive shaft torques during bus faults

A phase-to-phase or three-phase short-circuit at or near the synchronous motor terminals produces high shaft torques that can damage the motor or driven machine. Computer programs have been developed for calculating the torques. Refer to IEEE Std C37.96–2012 for information on this potential problem.

To reduce exposure to damaging torques, a three-phase high-speed undervoltage element (Device 27) can be applied to detect severe phase-to-phase and three-phase short-circuit conditions for which the motors should be tripped. A severe reduction in phase-to-phase or three-phase voltage causes tripping. Add additional tripping delay of 15 ms to 150 ms may be satisfactory from a protection point of view and desirable to avoid unnecessary shutdowns. Consult the suppliers of the motor, driven machine, and protection devices when determining protection settings.

8.7 Starting protection

8.7.1 General

This section discusses incomplete start sequence protection and excessive starts (within a short time period). Many types of the protective devices discussed in 8.7.2 through 8.7.3 do not have operation indicators. Separate operation indicators should be used with these protective devices.

8.7.2 Incomplete starting sequence (Device 48)

8.7.2.1 Introduction

A timer, Device 48, is used to monitor the motor start time. A motor that takes too much time to start can be damaged by excessive heating. The timer is initiated by an auxiliary contact on the motor starter, and it times for a preset interval (that has been determined during test starting) to be slightly greater than the normal interval from start to reaching normal operation.

8.7.2.2 Device 48, synchronous motor protection

For synchronous motor applications, incomplete starting sequence protection (Device 48) is normally a timer that blocks tripping of the field-current failure protection and the pullout protection during the normal starting

interval. The timer is started by an auxiliary contact on the motor starter, and it times for a preset interval that has been determined during test starting to be slightly greater than the normal interval from start to reaching full field current. The timer puts the field-current failure and pullout protection in service at the end of its timing interval. This timer is often a de-energize-to-time device so that it is fail-safe with regard to applying the field-current failure and pullout protection.

8.7.2.3 Device 48, induction motor protection

For induction motor applications, incomplete starting sequence protection (Device 48), wound-rotor induction motors and motors with reduced-voltage starting should have a timer applied to protect against failure to reach normal running conditions within the normal starting time. Such a de-energized-to-time device is started by an auxiliary contact on the motor starter and times for a preset interval, which has been determined during test starting to be slightly greater than the normal starting interval. The timer trip contact is blocked by an auxiliary contact of the final device that operates to complete the starting sequence. This device would be the final secondary contactor in the case of a wound-rotor motor, or it would be the device that applies full voltage to the motor stator. Incomplete sequence protection should also be applied to split-winding and wye-delta motor-starting control, as well as to pony motor and other reduced-voltage sequential start schemes.

8.7.3 Protection against excessive starting (48, 49, 51LR, and 66)

The following protections against excessive starting are available:

a) A timer element, started by an auxiliary contact on the motor starter, with contact arranged to block a second start until the preset timing interval has elapsed (Device 48).
b) Stator thermal overload element (Device 49S). This protection depends upon the following:
    1) The normal duration and magnitude of motor inrush
    2) Running thermal capacity previously developed
    3) The thermal amortisseur-winding protection on synchronous motors
    4) Rotor overtemperature protection (49R)
c) Time overcurrent protection for locked rotor protection is set below the expected locked rotor current with a time delay less than the thermal capability curve of the motor (Device 51LR).
d) Multifunction motor protection relays that have the capability to be programmed to limit the number of starts during a specific period (jogging protection). Large motors are often provided with nameplates giving the permissible start frequency (Device 66).

8.8 Rotor winding protection

8.8.1 Synchronous motors

The field and field supply should not be grounded intentionally. While the first ground connection does not cause damage, a second ground connection will cause damage. Therefore, detecting the first ground is important. The following methods are used:

a) Connect two lamps in series between field positive and negative with the midpoint between the lamps connected to ground. A ground condition shows by unequal brilliance of the two lamps.
b) Connect two resistors in series between field positive and negative with the midpoint between the resistors connected through a suitable instantaneous relay to ground. The maximum resistance to ground that can be detected depends upon the relay sensitivity and the resistance in the two resistors. This scheme does not detect a ground fault at midpoint in the field winding. If a varistor is used instead of one of the resistors, then the point in the field winding at which a ground fault cannot be detected

changes with the magnitude of the excitation voltage. This approach is used to overcome the limitation of not being able to detect a field midpoint ground fault.

c) Apply low ac voltage signal between the field circuit and ground, and monitor the ac flow to determine when a field-circuit ground fault occurs. Before using this scheme, a determination should be made that a damaging ac current will not flow through the field capacitance to the rotor iron and then through the bearings to ground and thus cause damage to the bearings.

If a portion of the field becomes faulted, damaging vibrations can result. Vibration monitors and sensors should be considered.

8.8.2 Wound-rotor induction motors

The protection for wound-rotor induction motors is similar to the protection described for synchronous motors, except the field is three-phase ac instead of a dc field (see Figure 40). Yuen, et al. [B69], describe some operating experience that confirms the effectiveness of this protection. Wound-rotor motor damage can result from high-resonant torques during operation with unbalanced impedances in the external rotor circuit on speed-controlled motors. Protection to detect this fault is available, although it is seldom used.

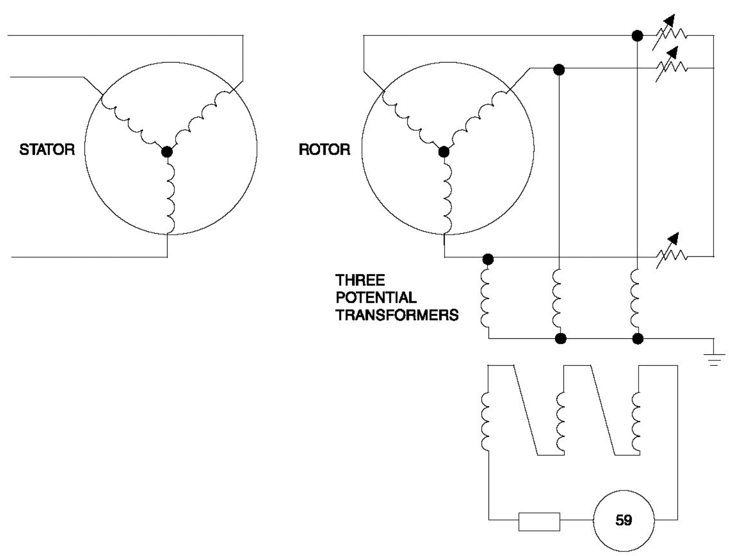


Figure 40—Rotor ground protection of wound-rotor motor

8.9 Lightning and surge protection

8.9.1 Types of protection

Surge arresters are often used, one per phase connected between phase and ground, to limit the voltage to ground impressed upon the motor stator winding from lightning and switching surges. The need for this type of protection depends upon the exposure of the motor and the related power supply to surges. MV cables have capacitance in their shields that can attenuate a surge. Like many protection applications, the engineer should consider motor importance, process downtime and associated costs, and replacement costs. A study is recommended.

The coil insulation of the stator winding of ac rotating machines has a relatively low impulse strength. Stator winding insulation systems of ac machines are exposed to stresses from the steady state operating voltages and

from steep wave-front voltage surges of high amplitudes. Both types of voltages stress the ground insulation. Steep wave-front surges also stress the turn insulation. If the rise time of the surge is sufficiently steep (i.e., 0.1 µs to 0.2 µs), then most of the surge can appear across the first coil and the line-end coil; whereas, its distribution in the coil can be nonlinear. This phenomenon can damage the turn insulation even though the magnitude of the surge is limited to a value that can be withstood safely by the ground-wall insulation.

The surge arrester should be selected to limit the magnitude of the surge voltage to a value less than the motor insulation surge withstand voltage by present standard tests described in Figure 7 of IEEE Std C37.96–2012 and Table 8. The steepness of the surge wave-front at the motor terminals is influenced by two time constants:

— At the supply end, by the effect of system inductance, grounding resistance, and motor cable impedance
— At the motor end, by cable impedance and motor capacitance

Surge capacitors are used, also connected between each phase and ground, to decrease the slope of the wave-front of lightning and switching surge voltages. As the surge voltage wave-front travels through the motor winding, the surge voltage between adjacent turns and adjacent coils of the same phase are lower for a wave-front having a decreased slope. (A less-steep wave-front is another way of designating a wave-front having a decreased slope.) The recommended practice is to install a surge-protection package consisting of a three single-phase capacitors and three surge arrestors.

Table 8—The equivalent motor insulation surge withstand voltage by present standard test for commercially used motor voltages

Rated voltage (V)	NEMA (kV)	IEC (kV)
2400	9	15
4160	15	22
13 800	51	60

The steep wave-front surges appearing across the motor terminals are caused by lightning strikes, normal circuit breaker operation, motor starting, aborted starts, bus transfers, switching windings (or speeds) in two-speed motors, or switching of power factor correcting capacitors. Turn insulation testing also imposes a high stress on the insulation system.

The crest value and rise time of the surge at the motor depend on the transient event, on the electrical system design, and on the number and characteristics of all other devices in the system. These factors include, but are not limited to, the motor, the cables connecting the motor to the switching device, the conduit and conduit grounding, the type of switching device, the length of the switchgear bus, and the number of other circuits connected to the bus.

See IEEE Std C37.96–2012 for additional information on recommendations from the IEEE Surge Protection Committee.

8.9.2 Locations of surge protection

The surge protection should be located as close to the motor terminals (in circuit length) as feasible, preferably with leads of 1 m or less. The supply circuit should connect directly to the surge equipment first and then go to the motor.

Specifying that the surge protection be supplied in an oversized terminal box on the motor or in a terminal box adjacent to the motor is becoming more common. When surge protection is supplied in a motor terminal box, it must be disconnected before high-voltage dielectric testing of the motor begins. This step is a recognized inconvenience of this arrangement. A separate surge disconnecting device may be required.

If the motors are within 30 m of their starters or the supply bus, locating the surge arresters, but not capacitors, in the starters or supply bus switchgear is economical (but not as effective). In the latter case, one set of surge protection can be used for all the motors within that 30 m of the bus. Alternatively, this approach can be used for the smaller motors, and separate surge protection installed at each larger motor. Neither of these remote methods is recommended. Also, locating the surge protection at the line side of the motor disconnect is not recommended because the disconnect and surge protection might be too distant to be effective.

8.9.3 Application of surge protection

The following factors should be considered when applying surge protection:

a) When a MV motor is rated above 375 kW (500 hp), surge arresters and capacitors should be considered.

b) For motors rated 375 kW (500 hp) and below, the need for surge arresters should include consideration of the higher surge impedance for these motors.

c) When a 150 kW (200 hp) or larger motor or when a critical motor is connected to open overhead lines at the same voltage level as the motor, surge arrestors and capacitors should be considered.

d) Even when a transformer is connecting the motors to open overhead lines, surge protection is still required at times to protect against lightning or switching surges. Techniques are available to analyze this situation. If uncertain, surge protection should be provided. Refer to 8.9.2 for surge protection on the supply bus for motors located remote from the bus. In addition, refer to Chapter 13 and Chapter 14 of IEEE Std 242-2001, which recommend protection for switchgear and incoming lines.

e) Where certain vacuum or SF_6 circuit breakers or vacuum contactors are used, surge protection may be necessary because of the possibility of restrikes, which can result in voltage spikes.

f) For application in Class I, Division 2 or Class I, Zone 2, nonsparking surge arresters, such as metal oxide varistor (MOV), sealed type, and specific duty surge protective capacitors can be installed in general-purpose type enclosures. Surge protection types other than those described above require enclosures approved for Class I, Division 1 locations or Zone 1 locations (NFPA 497-2008 [B47]). (See 2014 NEC Article 501.35(B) and 505.20(C). Refer to IEEE Std 1349-2011.)

NOTE 1—For a motor application, using three single-phase specific duty surge capacitors avoids phase-phase short-circuit faults within the capacitor.

NOTE 2—To direct hot gases from an arc flash that may occur in the motor terminal box, rupture panels can be installed to direct the hot gases away from the front of the motor and away from personnel. See Murfield, Zettervall, and Lockley [B39].

8.10 Protection against overexcitation from shunt capacitance

8.10.1 Nature of problem

When the supply voltage is switched off, an induction motor initially continues to rotate and retain the internal voltage. If a capacitor bank is left connected to the motor or if a long distribution line having significant shunt capacitance is left connected to the motor, the possibility of overexcitation exists. Overexcitation results when the voltage versus current curves of the shunt capacitance and the motor no-load excitation characteristic intersect at a voltage above the rated motor voltage.

The maximum voltage that can occur is the maximum voltage on the motor no-load excitation characteristic (sometimes called magnetization or saturation characteristic). This voltage, which decays with motor speed, can be damaging to a motor (see Figure 41 as an example).

Damaging inrush can occur if automatic reclosing or transfer takes place on a motor that has a significant internal voltage from overexcitation.

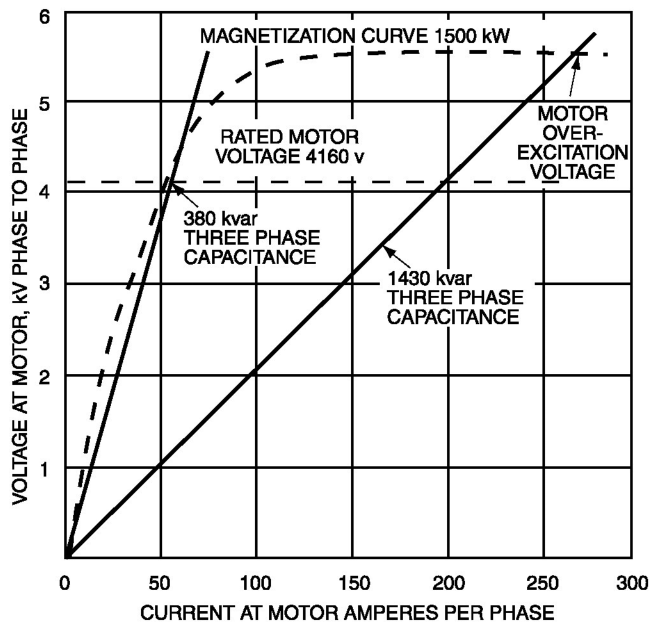


Figure 41—Excess shunt capacitance from utility line, which is likely to overexcite a large high-speed motor

8.10.2 Protection

When overexcitation is expected, protection can be applied in several ways. Beginning with the simplest protection, a separate contactor drops out the capacitors when the motor power source is lost. The contactor could also be dropped out by instantaneous overvoltage relay elements. An alternative is to use a high-speed underfrequency relay, which, however, might not be sufficiently fast enough on high-inertia or lightly loaded motors.

The underfrequency relay is not suitable for motors when frequency might not decrease following loss of the supply overcurrent protective disconnecting device. With these applications, a loss-of-power relay could be used. Examples of these applications are as follows:

a) Mine hoist with overhauling load characteristic at time of loss of supply overcurrent device
b) Motor operating as induction generator on shaft with process gas expander
c) Induction motor with forced commutation from an ASD

8.11 Protection against failure to rotate

8.11.1 Failure to rotate

A failure to rotate occurs when the supply is single phased or if the motor or driven machine is jammed. The following protection is available:

a) Relays can be used to detect single phasing (see 6.3.2).

b) The direct means to detect failure to rotate is to use a shaft-speed sensor and timer to check whether a preset speed has been reached by the end of a short preset interval after energizing the motor. This protection may be necessary for induction and brushless synchronous motors that have a permissible locked rotor time less than normal acceleration time.

c) For induction and brushless synchronous motors having a permissible locked rotor time greater than normal acceleration time, relying upon the thermal overload element (Device 49TC) is preferred. Using an inverse-time phase-overcurrent element (Device 51) as a backup is normal (see 6.4 and 6.5).

d) For brush synchronous motors having a permissible locked rotor time less than normal acceleration time, one method of protection is to use a frequency-sensitive relay connected to the field discharge resistor and a timer because the frequency of the induced field current flowing through the discharge resistor is related to the motor speed. A frequency-sensitive adjustable time-delay voltage relay is also available to provide this protection.

e) For brush synchronous motors having a permissible locked rotor time greater than normal acceleration time, relying upon the damper-winding protection and incomplete starting sequence protection is normal.

f) For a large induction motor protection to start, an impedance element (Device 21) can be applied (see 8.3, Figure 25, and Figure 26).

8.11.2 Reverse rotation or loss of phase

A reversal in phase rotation or a loss of phase can be detected by a reverse-phase voltage element (Device 47) [see 6.3.1 e) and Figure 10] if the reversal or loss occurs in the system on the supply side of the relay. This relay element cannot detect a reversal or loss that occurs between the motor and the point at which the relay element is connected to the system. Set this element for no more than 5% voltage imbalance. Unbalanced voltages create large unbalanced currents (approximately six to 10 times the percent voltage unbalance per NEMA MG-1-2011, 14.36.5); these negative sequence currents can damage motor stator windings.

A backup method for reducing unbalanced power system damage is using a current-unbalance element (Device 46) [see 6.3.1 a) and Figure 10]. Set this element to 0.2 pu negative sequence current.

A directional speed switch mounted on the shaft and a timer can be used to detect starting with reverse rotation. Some motor loads are equipped with a ratchet arrangement to prevent reverse rotation.

Alternatively a machinery protection system may be used with a speed monitor to detect reverse rotation (see 8.5.5)

9. Protection for ac ASD applications

9.1 ASD general information

9.1.1 Introduction

Motors fed from non-sinusoidal sources require careful consideration of the components of the system including the motor, cables, adjustable speed drive (ASD), power source, and protection devices and settings. Clause 5 presents factors to consider in protection of motors whereby these factors also apply to ASD applications.

This section covers ASD general information, LV and MV ASD applications. This section covers some basic information for ASD applications including terminology, motor selection, ASD selection, filters and reactors,

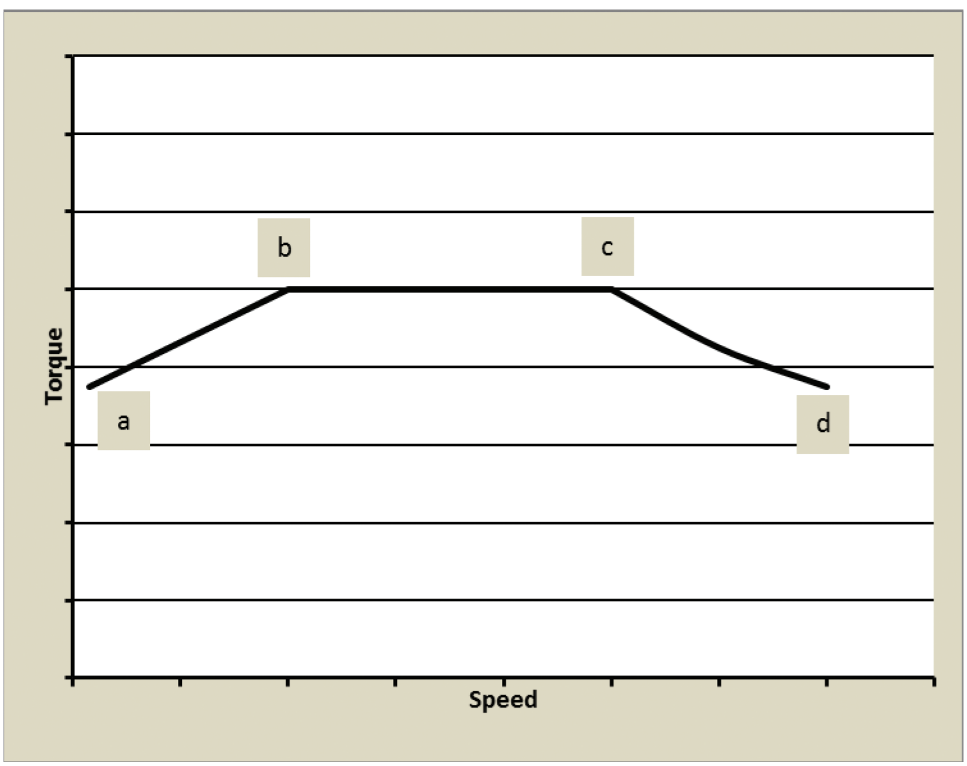
regeneration and dynamic braking, and auxiliary monitoring of ASDs. Refer to Chapter 4 of IEEE Std 242-2001 for a discussion of Zones of Protection.

9.1.2 ASD terminology

There is no single industry recognized name for adjustable speed drives (ASDs), which is the IEEE preferred terminology and will be used in this document. ASDs are ac or dc drives and are also called variable speed drives (VSDs). Several terms describe ac ASDs only: adjustable frequency controller (AFC), adjustable frequency drive (AFD), variable frequency drive (VFD) and power conversion equipment. A *power converter* converts ac to dc; and an *inverter* inverts dc to ac: ASDs discussed in this section may be current source, voltage source, or pulse-width modulation (PWM).

9.1.3 NEMA MG-1 Part 30 and 31 inverter duty

NEMA MG-1-2011 Part 30 covers application considerations for motors operated at constant speed with sinusoidal power or with ASDs. A motor should be selected to operate at or below its nameplate power rating over the entire speed range for the specific application. The power rating (hp or kW) available will be proportional to the decrease in frequency (directly proportional for constant torque and cubed for variable torque). Above rated frequency, the motor is capable of the rated nameplate power (hp or kW). Motor design and manufacturing standards address issues of concern for motors operating on non-sinusoidal power. A motor on an ASD will have a speed versus torque characteristic that is different than sinusoidal power. Refer to Figure 42 and NEMA's Application Guide for AC Adjustable Speed Drive Systems for an illustration and discussion of the motor speed versus torque characteristic when operated on an ASD [B42].



a = Torque at minimum speed based on temperature considerations and voltage boost

b = Lowest speed of the constant torque range based on temperature considerations

c = Base rating point at upper end of constant torque range

d = Maximum operating speed based on constant horsepower and any limitation on rotational speed

Figure 42—Motor speed versus torque for adjustable speed drive power (NEMA 2007 [B42])

NEMA has recognized the elevated stresses imposed on induction motors by adjustable frequency controls and has developed a performance standard for motors that are specifically identified as "inverter duty" or "inverter rated." Part 31 of NEMA MG-1-2011 addresses issues of particular concern to ASD-fed motors such as basis of rating over a speed range, thermal aging of insulation for operation at different loads and speeds, minimum breakaway and breakdown torque requirements, overload and overspeed capabilities, voltage spikes, and vibration, among others. Of unique pertinence to such definite-purpose motors is the ability to better withstand the repetitive voltage spikes that are characteristic of modern, fast-switching devices used in adjustable frequency controls.

An example of a typical LV ASD is shown in Figure 43. In addition to NEMA, other motor standards that address ASD applications include IEEE Std 841, API Std 541 5th Edition, API Std 546 3rd Edition, and API Std 547 1st Edition. ASD applications in Classified (hazardous) locations are discussed in Clause 11 of this standard and in IEEE Std 1349-2011.

Courtesy of Schneider Electric.

Figure 43—Typical LV adjustable speed drive

9.1.4 Selecting drives

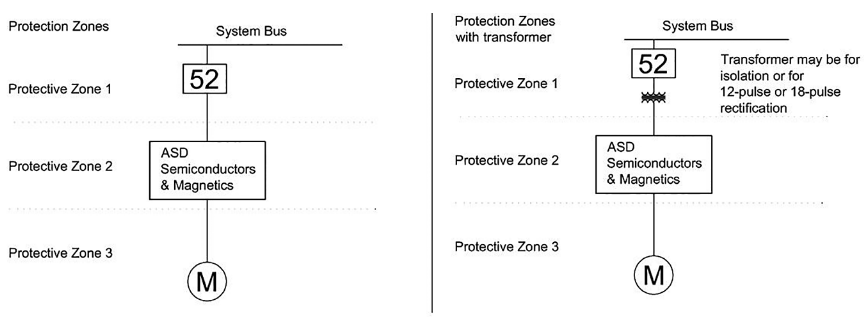
Clause 5 presents factors to consider in protection of motors whereby these factors also apply to ASD applications. Also refer to IEEE Std 1566™ for MV ASD selection and purchasing information [B31]. In Torres, et al. [B63] examples of motor torque versus speed with ASD applications are given; and in Hickok [B19] examples of load characteristics for ASD applications are given for pumps, fans, blowers, and compressors. When selecting an ASD, some considerations are also as follows:

— Load characteristics

— Motor nameplate data

— Motor speed control range, heating and performance considerations
— Breakaway torque requirements
— Load acceleration/deceleration requirements
— Environment (temperature, altitude, humidity)
— Multimotor or single motor
— Power system (voltage, harmonics, short-circuit current)
— NEC or other code requirements
— Application considerations (motor cable lead length and configuration)

Limiting system harmonics can be a significant factor for selecting a drive. Figure 44 a) is based on a 6-pulse drive system. Refer to Figure 37 for a more detailed example of a 6-pulse MV ASD. Refer to Figure 44 b) showing a 12-pulse system. The protection is identical because the 12-pulse consists of two 6-pulse channels operating simultaneously, with the input source voltage shifted by 30 degrees. In many instances, however, the input isolation transformer is a three-winding transformer with one secondary winding connected in delta, and the other secondary connected in ungrounded wye to obtain the 30 degree phase shift. This is done to significantly reduce the formation of harmonics, where the higher the pulse count the lower the harmonics. The transformer differential scheme would therefore include both secondary windings. The same philosophy would be used with drive systems with higher than 12-pulse designs. Drives use pulse counts that are multiples of 6, where a commonly used ASD today is 18-pulse, some are 54-pulse, and some may be higher.



a) Typical ASD zones of protection (6-pulse)

b) Typical ASD zones of protection (12- or 18-pulse with transformer)

Courtesy of Schneider Electric.

Figure 44—Typical adjustable speed drive zones of protection

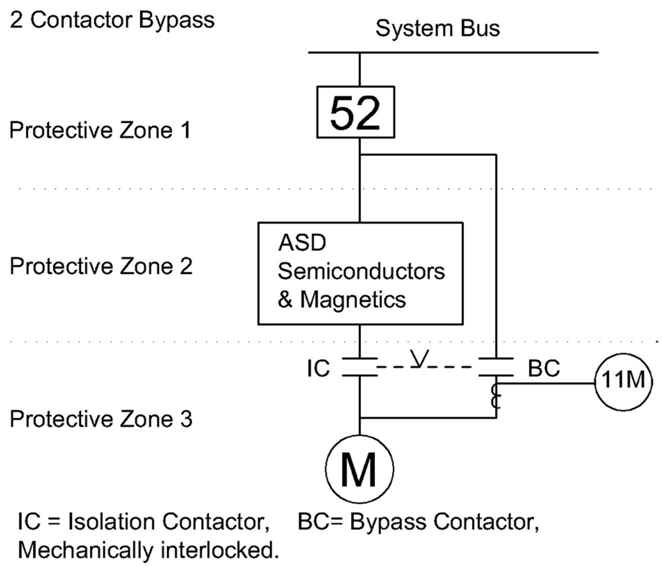
9.1.5 ASD bypass circuit protection

For ASD systems that utilize a bypass device to allow motor operation at rated full load speed, motor overload protection must be provided in the bypass circuit.

Bypass circuitry is usually accomplished using bypass contactors and are often used with AC drives. There are two reasons for bypass. The most common is for maintenance purposes. If the drive is out for maintenance, the bypass contactor is closed to allow the motor to run across the line (ATL). The motor is provided with motor protection while in bypass mode. To avoid damage to the ASD, the motor field should be allowed to decay for a minimum of three open-circuit ac time constants after disconnecting from line power and before reconnecting to the ASD. It also should be determined that the ASD has the capability of restarting a coasting motor before switching from line power back to ASD power while the motor is still rotating.

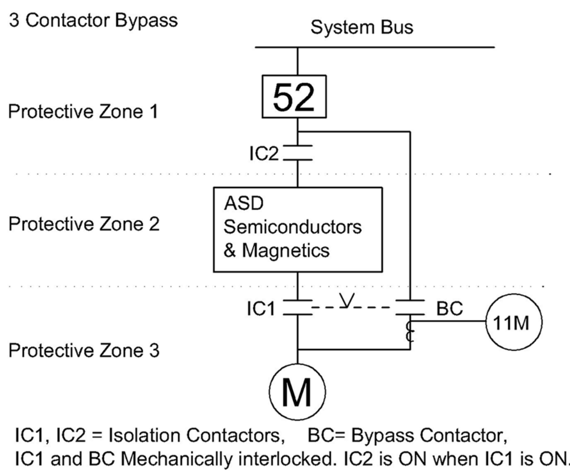
Another purpose for a bypass circuit is to allow the ASD to bring one motor to full speed and then switch to another motor, where this is known as synchronous transfer. This allows the user to have one drive for many motors. Refer to Figure 53 for an example of synchronous transfer.

Refer to Figure 45 and Figure 46 for two-contactor and three-contactor bypass systems, respectively. In Zone 1, the LV and MV protection schemes may vary.



Courtesy of Schneider Electric.

Figure 45—Two-contactor bypass system



Courtesy of Schneider Electric.

Figure 46—Three-contactor bypass system

9.1.6 ASD output filters and reactors

These load filters are typically required for long cable lengths and will further reduce the reflected wave amplitude seen on the cable and increase cable life.

Reflected wave voltage spikes can damage the motor winding, especially the first turns of a winding. NEMA's "Application Guide for AC Adjustable Speed Drive Systems" [B42] section 5.2.9 addresses this phenomenon. Several factors, including pulse rise time, cable length, minimum time between pulses, minimum pulse duration, transition type (single or double), and the use of multiple motors affect the peak voltage at the motor's terminals. Some ASDs allow adjustments for the minimum time between pulses and/or minimum pulse durations in order to reduce the magnitude of the reflected wave voltage spikes.

If the motor cable length is long enough to cause the reflected wave voltage spikes that could damage the motor, then an output reactor can be used to attenuate the peak voltage. A reactor with impedance of 1.5% is often sufficient to reduce the voltage spikes although some manufacturers use 3% if the voltage drop can be tolerated. For longer runs a dV/dt filter can be used. These filters have a 1.5% reactor and an RC snubber circuit to increase the rise time of the pulses, thereby reducing the dV/dt. For very long cable runs, a sinewave filter is generally used to attenuate voltage spikes. These have multiple stages of inductors and capacitors and significantly filter out the PWM leaving a sinusoidal voltage to go to the motor. The reactor filter, dV/dt filter, and sinewave filter are progressively more costly, respectively.

9.1.7 Overtemperature and overload protection

Overheating of motors can occur even at current levels less than a motor's rated full load current. Overheating can be the result of the shaft-mounted fan operating at less than rated nameplate RPM. For motors that utilize external forced air or liquid cooling systems, overtemperature can occur if the cooling system is not operating. In these instances, overtemperature protection using direct temperature sensing is recommended, or additional means should be provided to verify that the cooling system is operating (flow or pressure sensing, interlocking of ASD system and cooling system, etc.).

ASD systems must protect against motor overtemperature conditions where the motor is not rated to operate at the nameplate rated current over the speed range required by the application. Such protection may be provided by the following:

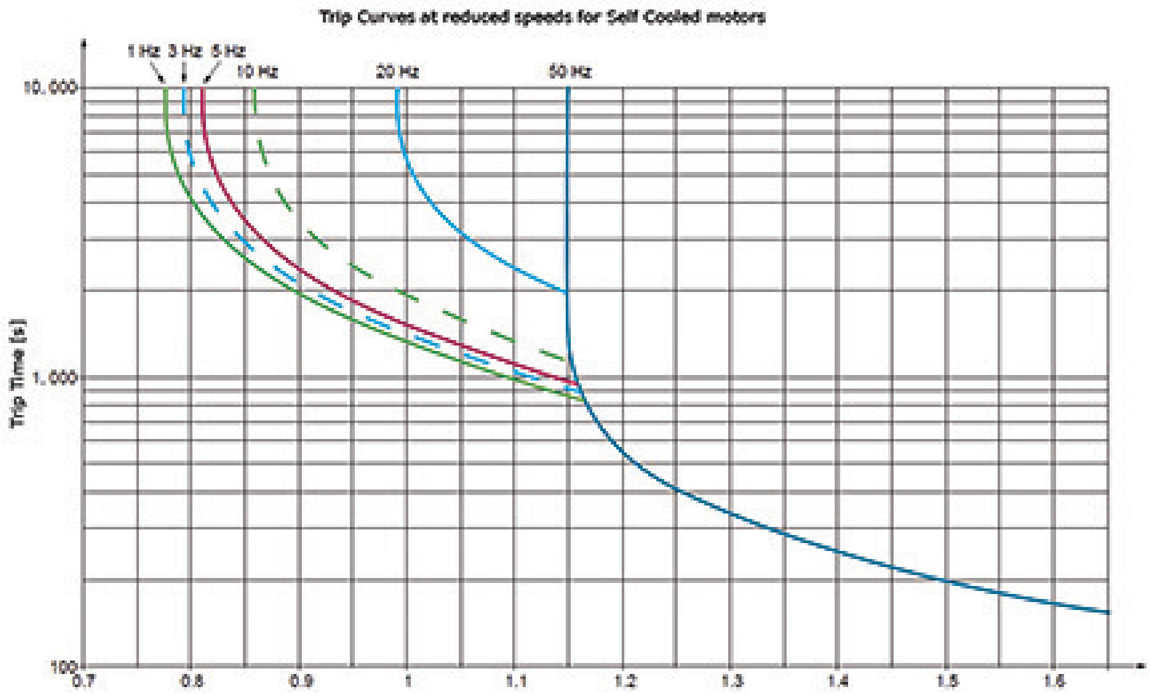
- Motor thermal protector in accordance with NEC Section 430.32
- ASD system with load- and speed-sensitive overload protection and thermal memory retention upon shutdown or power loss, except that thermal memory retention upon shutdown or power loss is not required for continuous duty loads
- Overtemperature protection relay utilizing thermal sensors embedded in the motor and meeting the requirements of NEC Sections 430.32(A)(2) or (B)(2)
- Thermal sensor embedded in the motor whose communications are received and acted upon by an ASD system

For multiple motor applications, individual motor overtemperature protection shall be provided as required in NEC Section 430.126(A).

When running an ASD at the rated frequency of 50 Hz or 60 Hz, a standard overload curve can be used as shown in Figure 6 by the 50 Hz line where the Class 10 overload would trip in 10 s at 6 times rated current. The starting/maximum current setting for a typical ASD may be in the range of 115% to 170% of nameplate rated current. Figure 47 expands the main area of interest for the ASD application.

A motor cooled by a separate blower can also be protected by a separate overload such as Class 10 bi-metallic overload relay or built-in to the software and electronics of the internal overload of the ASD. However, when running at reduced speeds, self-cooled motors cannot generate as much air flow as they can at rated speed, and the motor may overheat at lower current levels. Reduced speed overheating is more common for constant torque applications versus variable torque applications. All applications have minimum time limits at various speeds to maintain adequate cooling.

Some ASD internal overloads take this reduced cooling at slower speeds (lower frequency) into account and adapt the overload curves for lower speed operation.



Courtesy of Schneider Electric.

Figure 47—Typical ASD internal overload protection for self-cooled motors

The *x* axis is the ratio of the actual current to rated current of the motor, the full load current (FLC). The 50 Hz curve represents the nominal frequency of the motor, either 50 Hz or 60 Hz. The lower speed curves show the levels at which the electronic overload would trip to protect the slow-turning motor, even though the current could be less than the rated FLC of the motor.

Where the ASD is marked to indicate that motor overload protection is included, additional overload protection is not required if the overload protection is sized to protect the motor for a specific application.

If the ASD manufacturer does not provide an overload that can adapt the trip curve depending on the speed of the self-cooled motor, then direct measurement of the motor winding temperature should be accomplished by positive temperature coefficient resistors (PTC), thermocouple devices, thermal switches, or RTD sensors with a relay to trip on overtemperature. Refer to 7.4.3 for more information on PTC devices.

9.1.8 Regeneration and dynamic braking

Most adjustable speed drives can provide a controlled speed deceleration of the connected load. However, for very fast stopping requirements, alternative braking systems may be required. In some applications, the controlled deceleration time of the motor and load combination can be excessive and can present concerns for some situations. In the event of an emergency stop, the input and/or output power from the drive are removed. The connected load may continue to rotate and coast to a stop, after the removal of power, due to the load inertia. If an immediate or emergency stop of rotation of the motor and connected load is required, a braking method must be used. The most common types of motor braking systems, available with some ASD, are dynamic braking and dc injection braking systems.

A dynamic braking system converts the energy being regenerated from the rotating motor and connected load into heat that is dissipated through a connection to motor-braking resistors suitably sized to the load. Using dynamic braking stops the motor at the fastest rate allowed by the load but it cannot act as a holding brake. Dynamic braking should not be considered if the connected load typically operates at slow speeds (generally at less than 10 Hz) and braking is required. The dynamic braking system or ASD braking parameters should be configured to limit the application time of the external resistors in the event of a system malfunction as excessive amounts of heat energy will be generated in the event of an extended overcurrent condition. Alternative control methods can include braking application contactors, with control circuits configured with resistor thermal sensors and/or braking current overload protection, which, in the event of an extended overcurrent condition, would open the connection to the braking resistors. The protection mode in these cases is to protect the braking resistors from excessive currents or a duty cycle longer than their designed level.

A dc injection braking system applies dc current, sourced from or controlled by the drive, which is quickly applied to the stator windings of the motor. The ASD typically will include parameters for the control of the application time and braking current applied. The programmed level of the dc current and application time determines how fast the motor will decelerate and come to a stop. For slow-speed loads, dc injection will be the most effective braking method as it does not rely on the regenerative energy, from the motor, to provide the braking energy. Many dc injection braking systems can be configured to also prevent the rotor from spinning freely when the main power is removed from the motor; typically, dc injection can’t hold the load, but only slow it down. It is recommended that some level of overtemperature protection be incorporated in the motor and tied back to the dc injection system, because the application of the dc current does generate significant heat within the motor. Because of this, some systems can also be configured to provide a level of motor preheating.

NOTE—A mechanical brake is generally used to hold a load.

9.1.9 Protection device monitoring by auxiliary control equipment

In some applications, vibration and temperature-monitoring devices may be monitored by an auxiliary control panel; e.g., compressor or pump unit control panel, distributed control system (DCS), or station control panel. In these applications, permissive to start, alarm, and shutdown signals should be coordinated with the drive to protect the motor and the driven equipment.

9.2 Low voltage ac ASD motor protection

9.2.1 General

Refer to Figure 44 for the typical zones of protection for a LV ASD application. The LV breaker in Zone 1 protects the cable feeding the ASD and provides short-circuit protection for the ASD. Refer also to NEC Article 430 and Sections 430.52(C)(5) and 430.130. The internal software and electronics of the ASD typically provide overload and overtemperature protection for the motor. In addition, the ASD has current limit features providing short-circuit protection and detection, which trips/gates off the insulated-gate bipolar transistors (IGBTs) and isolates faults downstream. Overtemperature and overload protection is discussed in 9.1.7. It may be desirable to protect larger LV ac motors with protective relays. The manufacturer’s recommendations and literature should be used to select protective devices upstream of the ASD.

Zone 3 protection protects the motor and the cable feeding the motor. Conductors for LV ASD applications should be designed, tested, and installed for the service conditions. PD inception voltage can occur in LV ASD systems. The materials and methods should consider and mitigate possible PD effects.

9.2.2 LV ASD bypass motor protection

If a bypass system is used, motor protection is shown in Figure 44 and Figure 45. The manufacturer’s recommendations and literature should be used to select protective devices upstream of the ASD and for the bypass circuit. Refer also to NEC Article 430 and Sections 430.52(C)(5) and 430.130.

9.2.3 LV ASD multiple motor applications

For multiple motor applications, individual motor overload protection shall be provided in accordance with NEC Article 430, including NEC sections 430.130 and 430.131.

9.2.4 LV ASD ground fault protection for high resistance grounded systems

LV ASDs may have built-in ground fault protection; however, it may not be capable of detecting low-level ground faults and supplemental protection may be needed for reliable ground fault protection for high resistance grounded systems. Using a zero sequence CT connected to a ground overcurrent relay to detect small values of fault current in ASD circuits is accepted as a reliable approach; but where to locate the CT, upstream or downstream of the drive, is a matter of some debate. Specialized ac/dc ground fault relays (IEEE Device 50G or 51G and 76G) are available that can detect 0-Hz and higher-frequency faults using zero sequence CTs. The location of the CTs determines the protection zone. The location of the CTs is discussed in more detail in Savostianik, et al. [B54].

The high resistance ground should add sufficient neutral-to-ground resistance to limit the ground fault current to a value slightly higher than the system capacitive charging current (IEEE Std 142-2007 [B24], Skibinski, et al. [B57]). The zero sequence current flow through the resistor, ground fault-current levels on the load side, line side, and internal are used to select the protective device settings to trip without experiencing nuisance alarms. The decision to alarm and/or trip the ASD and a motor when a ground fault condition is detected should be evaluated for the application (Savostianik, et al. [B54]).

9.3 MV ac ASD motor protection

9.3.1 Introduction

The main objective of this section is to outline the general protection philosophies related to ac drive motor protection. Most ac drives use transformer-isolated frequency conversion circuitry to drive synchronous and induction motors and, therefore appear as transformer loads on the electrical system. It should be noted that these motors operate *asynchronously* from the electrical power system.

9.3.2 MV protection

Figure 48 illustrates a protection approach from an ASD application and can be used for guidance in the selection of adequate protection for motors used with ac drives. It should be noted that drives can have different topologies and components, therefore the selection of adequate protection needs to be based on the specific application and technologies used. Refer to IEEE Std 1566 for the performance of ASDs rated 375 kW and larger [B31].

The two MV ASD systems in common use are the induction motor drive and the synchronous motor drive. Both systems may include an input-isolation transformer, source-side converter, dc link reactor (and/or capacitors), load side inverter, and motor. The synchronous motor drive also includes an excitation system. The converters employ power electronic devices (such as thyristors) to control voltage and/or current. Other drive technologies would require similar protection considerations. These include pulse width modulated, voltage source inverter (VSI), and current source inverter (CSI) systems.

The drive system protection can be divided into the following three zones of protection as shown in Figure 48:

a) Zone 1: input zone (input transformers are included for some systems)

b) Zone 2: power electronics

c) Zone 3: motor

9.3.3 Protection commonly included in ASD

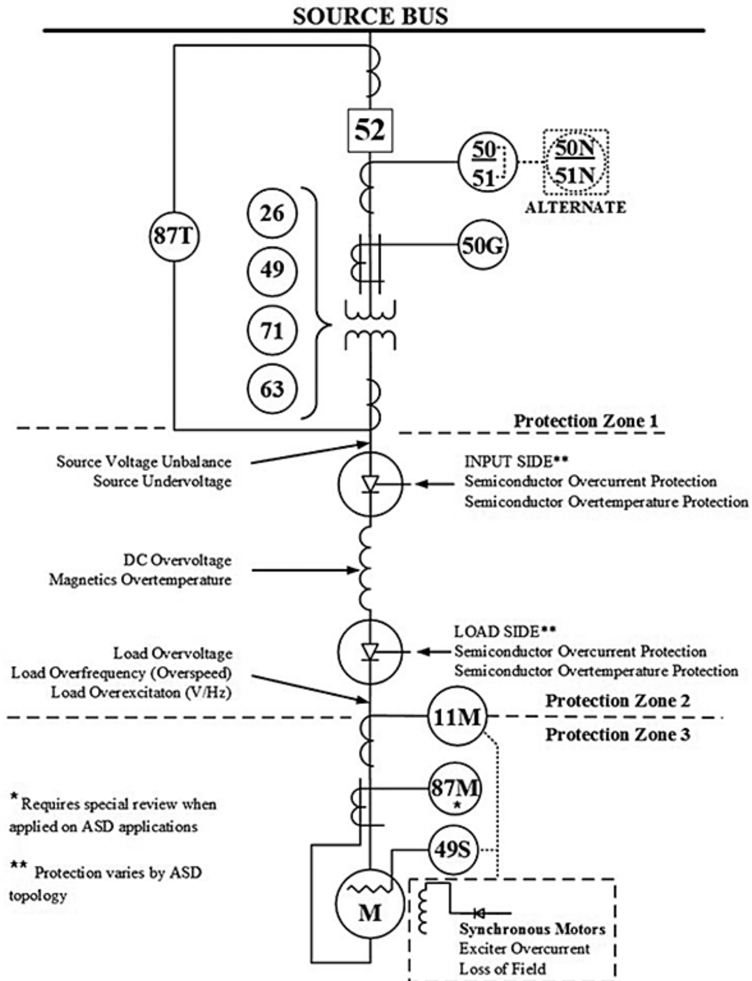
The protection elements included within the ASD controls vary from manufacturer to manufacturer. As shown in Figure 48, the protection can be broken down into three major categories, line side protection (Zone 1), system level protection (Zone 2), and load side protection (Zone 3). The following is the protection most commonly included in ASDs:

a) Line side protection (Zone 1)
   - Short-circuit/overcurrent: some are protected with a fuse, circuit breaker, or protective relay overcurrent function
   - Overload: overcurrent protection with time delay
   - Voltage unbalance: loss of input phase
   - Ground fault overcurrent

b) System-level protection (Zone 2)
   - DC overvoltage
   - DC undervoltage: loss of control power
   - Overtemperature: this includes the rectifier and inverter heat sinks as well as the enclosure temperature

c) Load side protection (Zone 3)
   - Ground fault
   - Motor overcurrent
   - Motor overload I^2t
   - Motor stall
   - Motor overspeed
   - Current unbalance
   - Under load: may indicate a process malfunction and will protect the machinery and the process in this fault condition
   - External fault: an external relay input
   - Motor differential
   - Overexcitation (V/Hz)
   - Vibration (8.5.5)
   - Overtemperature
   - Switching protection (snubber circuit)

Typically, ASDs offer a current limiter and torque limiter function. These functions can be programmed in order to keep the current and/or the torque at a maximum allowed limit. If the current or torque demand from the process or speed controller exceeds the current/torque limit, the actual speed is limited and the current/torque is kept below the limits. This function can be used to limit the current to the motor.



Courtesy of Rockwell Automation.

Figure 48—MV typical adjustable speed drive protection

9.3.4 Zone 1 protection

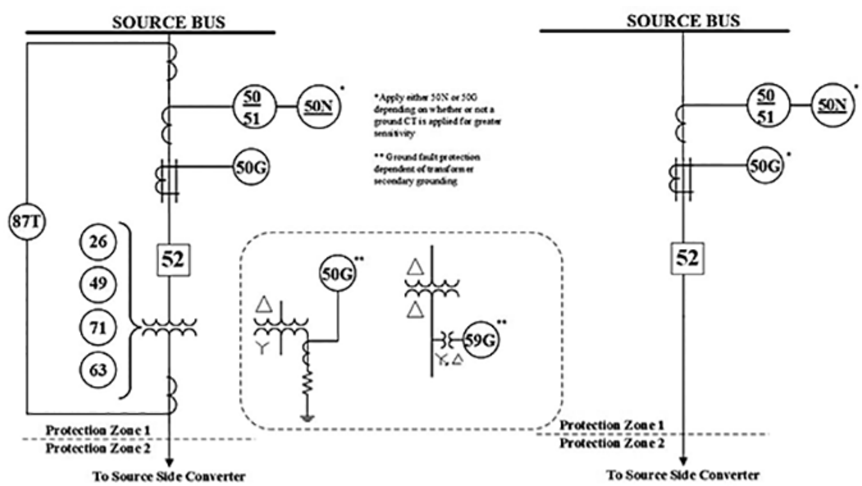
The feeder breaker supplying the ASD typically is equipped with overload and short-circuit protection for the input transformer and/or the drive electronics as shown in Figure 49. Typically, a phase time overcurrent element (51) is applied for overload protection and an instantaneous overcurrent element (50) short-circuit protection. A 51 element that operates on the fundamental frequency (i.e., not total rms) may be set with a lower pickup, as it will not respond to the harmonic components of the load current. If there is an isolation transformer, the 50 element is typically set at 140% of the transformer secondary through-fault current and above the transformer inrush current. In cases where the drive employs an active front-end the 50 element can be set lower as the drive normally limits the starting current to less than two times rated. Occasionally, a differential relay has been applied to the primary feeder to provide high speed tripping for faults up to the transformer high-side winding.

Differential protection for large isolation transformers can be considered, but may not be practical. For instance, in large ASD applications, the ASD isolation transformer typically has multiple secondary windings. In those cases, it is not practical to have conventional differential protection. The feeder overcurrent relay can then be relied upon to provide high speed protection for the isolation transformer primary windings. Relays which do not respond to dc offset currents should be selected to allow for the instantaneous element (50) to be

set as sensitive as possible. The feeder overcurrent (51) can provide conventional time-delayed protection. For multiple secondary winding configurations, the feeder overcurrent relay (51) may not provide protection for secondary winding faults. Differential protection (87T) may be needed for these applications. In some cases, the ASD integral protection includes a power differential that compares the transformer input and drive output power.

Where isolation transformers are used which have not been specifically designed for harmonic loading, IEEE Std C57.110™, "Recommended Practice for Establishing Transformer Capability when Supplying Non-sinusoidal Load Currents" [B33] may be used to apply transformer de-rating factors for each harmonic. Devices exist that will provide thermal protection based on this guide.

There may be additional protection applied for faults on the secondary side of the isolation transformer. This may include a zero sequence voltage detection circuit if the transformer secondary is ungrounded or a residual or neutral overcurrent for a grounded wye secondary connection. Some ASD manufacturers employ fuses for transformer through-fault protection.



Courtesy of Rockwell Automation.

Figure 49—Zone 1 protection with a transformer and ground fault protection; and without a transformer

9.3.5 Zone 2 protection

The firing of the thyristors is controlled by the ASD digital control system. The control system uses the input ac source voltage to determined proper firing angles and magnitudes. The control system is, therefore, sensitive to irregularities in the input voltage source. The control system monitors the ASD input and output voltages typically via voltage transformers and attenuating resistors. The control system includes minimum and maximum line voltage settings that actuate alarms and/or trips. In addition, under- and overvoltages are also monitored. Typical alarm settings would be 90% and 110%, respectively. Trip settings will vary depending on the manufacturer; however, a typical undervoltage trip setting would be in the range of 70% for 30 s, and a typical overvoltage setting would be in the range of 130% for a few cycles. Some manufacturers recommend more conservative settings in the range of 80% for 30 s and 120% for a few cycles, respectively. Some drives may also include dc link reactor overvoltage protection.

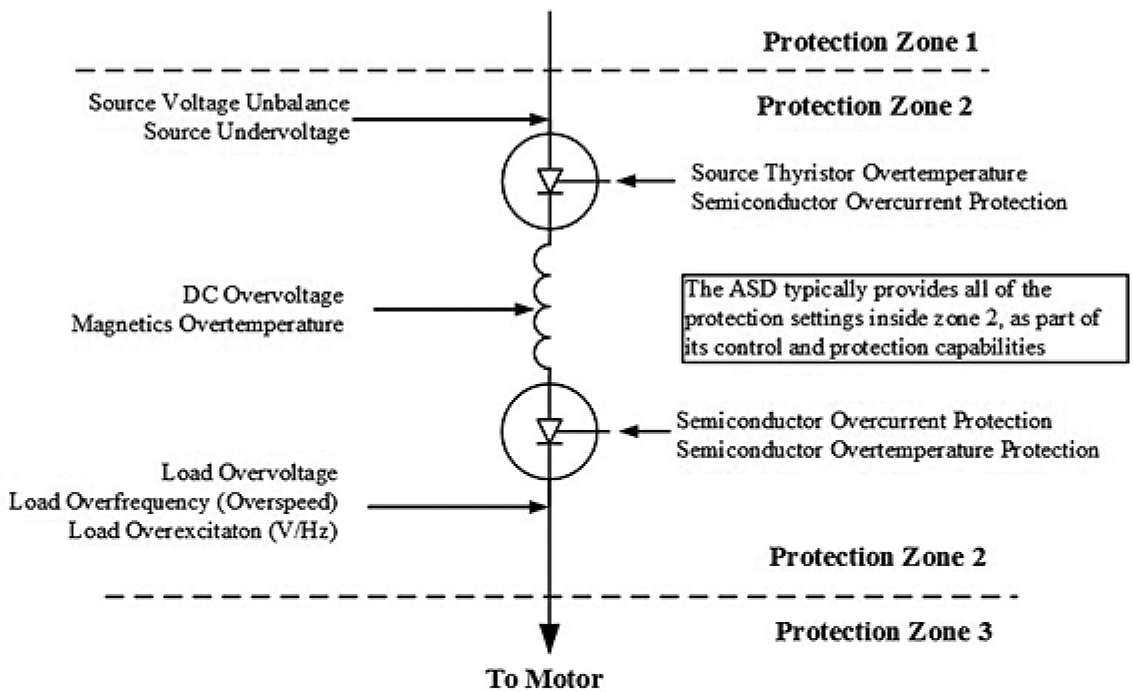
The dc link reactor between the input and output converters is subject to overtemperature during abnormal operation or inadequate cooling. Multiple temperature switches are typically provided to monitor reactor ambient temperatures. Alarm and trip settings are based on the reactor insulation rating. Some ASD systems include dc overvoltage detection. For example, an overvoltage detection results in the suppression of gate pulses to reduce dc link voltage. The control system monitors dc link voltage via a resistive divider. The exact setting of the dc overvoltage detection should be determined by the ASD system manufacturer.

Short-circuit protection is typically provided by fuses installed ahead of the thyristors. Opened fuse detection is provided by the ASD control system. Upstream protective relays should be coordinated with fuse characteristics.

Overcurrent protection is provided for the converter electronics and interconnected bus or wiring. Current levels are limited to acceptable levels by control action and the ASD is tripped if current is above these levels for a preselected time. During speed changes, allowable current levels are determined by the "current limit setting." During normal operation, current levels are typically limited to rated current. If currents remain above these levels for a predetermined time, the ASD is tripped.

Large ASD systems depend heavily on the ASD cooling system. Failure of the cooling system can cause overheating of the input and output converter thyristors in a few seconds. ASD can be air cooled or liquid cooled. In either case, temperature switches should be provided to monitor temperatures in the converter sections. In air-cooled designs, air-flow switches are usually provided to monitor cooling fan operation. Overtemperature indication or loss of cooling air flow typically would cause an ASD to trip.

See Figure 50 for the location of protective functions in Zone 2.



Courtesy of Rockwell Automation.

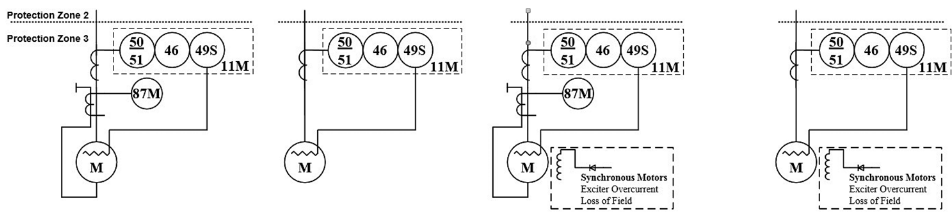
Figure 50—Zone 2 power electronics protection

9.3.6 Zone 3 protection

9.3.6.1 General

The motor should be provided with the same protection as constant speed motors of the same size. Figure 51 shows the protection functions which may be applied on the motor. In addition, because the motor may be particularly subject to abnormal voltage and frequency levels, motor protection should include overfrequency and overvoltage, or overexcitation (V/Hz). Separate V/Hz protection in addition to overvoltage and overfrequency is typically not required, because a failure of the V/Hz regulator would result in an overvoltage or overfrequency condition. The protection is typically provided by the drive control system but could be provided by discrete or multifunction relays. Motors that are "inverter duty rated" should be considered.

On critical motor installations, the use of a mechanical vibration detector is recommended. Machine harmonic currents from the drive output can lead to a net increase in repetitive motor vibrations and torque pulsations.



Courtesy of Rockwell Automation.

Figure 51—Zone 3 induction and synchronous motor protection with and without differential

ASD manufacturers typically integrate most of the required Zone 3 protection within the ASD internal electronics. Supplemental motor protection relays (e.g., separate relays), such as overcurrent protection and self-balancing differential protection (for large motors), may be considered. However, if applied, the off-frequency characteristics of the individual components comprising the supplemental relays should be carefully scrutinized to reduce false-tripping of Devices 51 or 87M. In particular, attention should be given to the low frequency saturation point of current transformers and the low frequency response characteristics of protective relays placed downstream of the ASD. A case study by Torres, et al. [B63] shows an ASD application where a phase reversal function (Device 47) on the output side of the ASD was counterproductive. Because of issues surrounding some protection functions, many ASD manufacturers do not recommend supplemental relays and warn of inadvertent tripping when they are used. In Torres, et al. [B63], a comparison of four vendors LV and MV ASDs is given in a table showing the Zone 2 protection features that may also protect the motor.

If supplemental relays are used with the ASD system, the items described in 9.3.6.2 through 9.3.6.7 should be considered.

9.3.6.2 Zone 3 overcurrent protection

In conventional motor protection, overcurrent curves are set to protect a motor based on its thermal limit curves. Time overcurrent curves are typically set below and to the left of these motor limit curves and above the acceleration curve to allow the motor to successfully accelerate.

Modern microprocessor based motor protection relays have thermal models which approximate the heating effects that various system conditions have on the stator and rotor. However, these thermal models rely on motor thermal damage curve limits which are typically reported by motor manufacturers at only nominal frequency 60 Hz. Unless the motor limits are known over the operating frequency range of the ASD, it may be difficult to fully utilize the thermal model available in many modern motor protective relays.

If the thermal model cannot be used, it may be more practical to use simple overcurrent relaying to provide motor overload protection. Either way, in this application, select a pickup based on motor FLC (corresponding to maximum operating frequency which will be close to nominal frequency). This will then provide overload current protection when the motor is operating at or near the maximum operating frequency but will provide reduced protection at lower frequencies.

If motor thermal limits are available at various frequencies, an alternative approach might be to implement adaptive characteristics which would provide full overload protection at all settings where different overcurrent curves are selected based on motor frequencies. Each overload curve would be applied to a band of frequencies and would be set to match the thermal limits of the motor at the upper range of the frequency band.

Overtemperature and overload protection are discussed in 9.1.7.

9.3.6.3 Zone 3 single-phase input protection

Single-phase operation will result in a significant increase in input rms currents, additional heating in the dc bus capacitors, and higher harmonic currents in the power distribution system. Most controls are equipped with single-phase protection to either reduce the load on the equipment or shut off the unit. Consult the manufacturer for proper guidelines and ratings.

9.3.6.4 Zone 3 ground fault protection

For Zone 1, the drive side of the isolation transformer typically has multiple secondary windings that are ungrounded, thus dedicated ground fault protection may not be practical. For Zone 2, the ASD provides internal ground fault protection. For Zone 3, during load side ground fault conditions, the ASD provides ground fault protection. A supplemental ground fault protection relay is typically not required unless the motor can also be started or operated across-the-line (bypassing the ASD).

9.3.6.5 Zone 3 CTs and relay harmonics

Care should be taken to select CTs that will not saturate over the expected operating frequency range of the ASD. The CT performance at low frequency/high harmonic content should be evaluated.

At reduced frequencies the CT capability is correspondingly reduced, e.g., at 10% frequency the CT capability is about 10%. However, the ASD load side fault current is relatively small (because of isolation from the ac system). Therefore the CT only has to be designed for motor contribution currents (relatively small currents). The relay performance should be considered over the operating frequency range and harmonic current exhibited on the output of the ASD. The use of a higher ratio CT and a lower nominal current relay (1 A CT and 1 A relay) would be an option to enhance overall CT/relay performance. The settings would be appropriately adjusted for those conditions.

9.3.6.6 Zone 3 motor differential protection

The most common motor differential is self-balancing and requires one CT per phase located at the motor as illustrated in 8.4.1.3. For conventional phase differential, one set of CTs is located on the load side of the ASD and the other set of CTs is located on the neutral side of the motor. Ideally, the CTs are a matched set with the same ratio and characteristics; otherwise, any differences in ratio or characteristics must be compensated for during both starting and running. There is a limitation on detecting differential current at lower frequencies due to the inherent characteristics of current transformers (Torres, et al. [B63]).

9.3.6.7 Zone 3 switching protection (snubber circuits)

When MV motors are switched with circuit breakers, switching may not occur at a natural current-zero point. If it occurs at natural current-zero, no harm occurs to the motor's windings. However, if current is interrupted

at a current-maximum, current-chopping occurs. A fast-rise-time, high-voltage transient is produced which can result in insulation breakdown.

Motors can be protected through use of a snubber. A snubber consists of a capacitor in series with a non-inductive resistor placed across the motor's terminals. The components can be purchased separately and assembled. Commercially available packages are also available. Some commercially available, packaged units also contain a zinc-oxide varistor placed in parallel with the resistor; the parallel combination is then placed in series with the capacitor. Note that a surge-capacitor alone will not fulfill this requirement.

Snubbers are connected from each motor lead to ground. For best protection, snubbers should be connected as close to the motor as possible. Because room is not normally available in the motor's junction box, snubbers are often mounted in a separate enclosure which is then mounted adjacent to the motor. The cable connecting the snubber assembly to the motor should be the same as the cable used to connect the motor to the circuit breaker. The manufacturers of the motor and ASD should be consulted for the recommended connections to ground.

When planning an installation employing MV motors switched by circuit breakers or other devices, a study should be considered. The snubber study will yield the need for a snubber, if any, as well as values for the resistance and the capacitance required. Not all installations require snubbers. The closer a breaker is located to a motor, the more likely will be the need for a snubber.

9.3.7 Additional factors that impact protection

When motors are applied to ASDs, certain operating characteristics of the motor are modified. The operating frequency affects how the motor behaves during operation—both starting and running—as well as during abnormal operation and fault conditions. The areas that will be discussed are pertinent to the protection of the motor and drive system. The following characteristics are pertinent to the protection of the motor:

a) *ASD ground fault conditions*: Two cases should be distinguished:

   1) ASD with input transformer. The input transformer provides galvanic isolation between the ASD and the feeder bus. A ground fault on the ASD will not influence the ground fault protection of the feeder bus (see Figure 48).

      NOTE—Except in the case of a wye-wye transformer, a ground fault on the ASD will not influence the ground fault protection of the feeder bus (see Figure 48). Wye-wye transformers are not typically used for ASD application because they do not provide the isolation or filter the third harmonics.

   2) ASD without input transformer. There is no galvanic isolation between the ASD and the network in this configuration. A ground fault on the ASD system may trigger the ground fault protection on the feeder bus. It is recommended to check the ground fault protection scheme of the ASD with the manufacturer to confirm selectivity of the ground fault protection scheme (ASD ground fault protection should trip faster than the feeder bus ground fault protection).

b) *Motor fault contributions*: When a drive is applied to a motor it provides a current-limiting feature such that it will limit the contribution to the system short-circuit level. In some cases, the contribution to short-circuit can be eliminated by switching the power electronics in the drive such that any short-circuit current contribution from the motor will not flow back to the point of fault in the system. This is a significant benefit with regard to a large motor with a long short-circuit time constant when considering limits on the system breakers for fault duties.

c) *Soft starting:* ASDs limit and control motor starting current by the appropriate firing of the power electronics. This capability is known as *soft starting*.

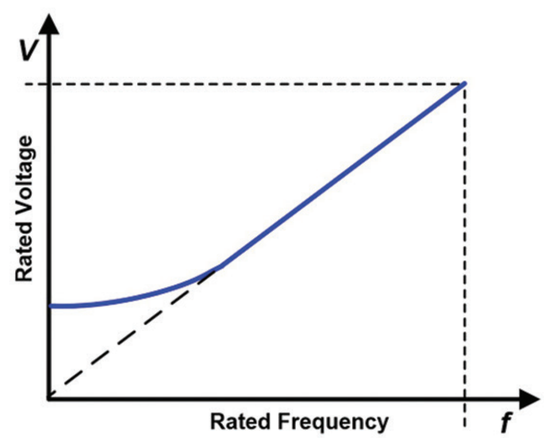
d) *Reduced frequency operation effects:* The frequency of the source to the motor dictates the operating speed. At lower speed operation the motor is not cooled as efficiently as it is at rated speed. Therefore, this should be taken into consideration with regard to motor thermal overload protection. For constant

torque applications, auxiliary motor cooling may be required. Actual motor full load current (FLC) is a function of the frequency, as lower FLC is drawn at lower frequency. The actual FLC should be used in the overload protection. This is particularly important for a sustained motor operation at off-nominal frequency. Note that motor manufacturers typically state rated FLC at nominal frequency. In addition, it is important that the protective device accurately measures motor current at off-nominal frequencies (by frequency tracking or other means) to provide effective overload protection at all frequencies.

e) *Harmonics:* Harmonics in the load side current will cause additional heating in the motors and other connected elements (e.g., conductors). This additional harmonic heating needs to be considered when sizing and protecting the equipment. Near rated load, a typical value to accommodate the additional heating can be a 15% increase above the fundamental heating effects or more; however with sine wave filters heating effects may be close to the fundamental heating effects. Refer to NEMA MG-1-2011 for further details or derating factors. Auxiliary cooling may be considered for constant torque applications.

f) *Flux levels:* State-of-the-art control algorithms used in ASDs keep the motor flux constant over the entire speed/frequency range. This results in a V/Hz excitation curve for an induction motor shown in Figure 52. The voltage is proportional to the frequency (V/Hz = constant) in the upper frequency range. In the lower frequency range, the voltage is not proportional to the frequency. An extra voltage boost is applied to compensate for the voltage drop over the stator resistance of the motor. This characteristic should be considered in sizing CTs and VTs.

g) *Voltage and dielectric stresses*: Overvoltage protection should be considered for drives applied on long cable runs, where cable capacitance along with fairly high semiconductor switching frequencies can result in sustained overvoltages. Resonance or transient overvoltages caused by switching should be mitigated by other means (e.g., dV/dt filters, etc.).



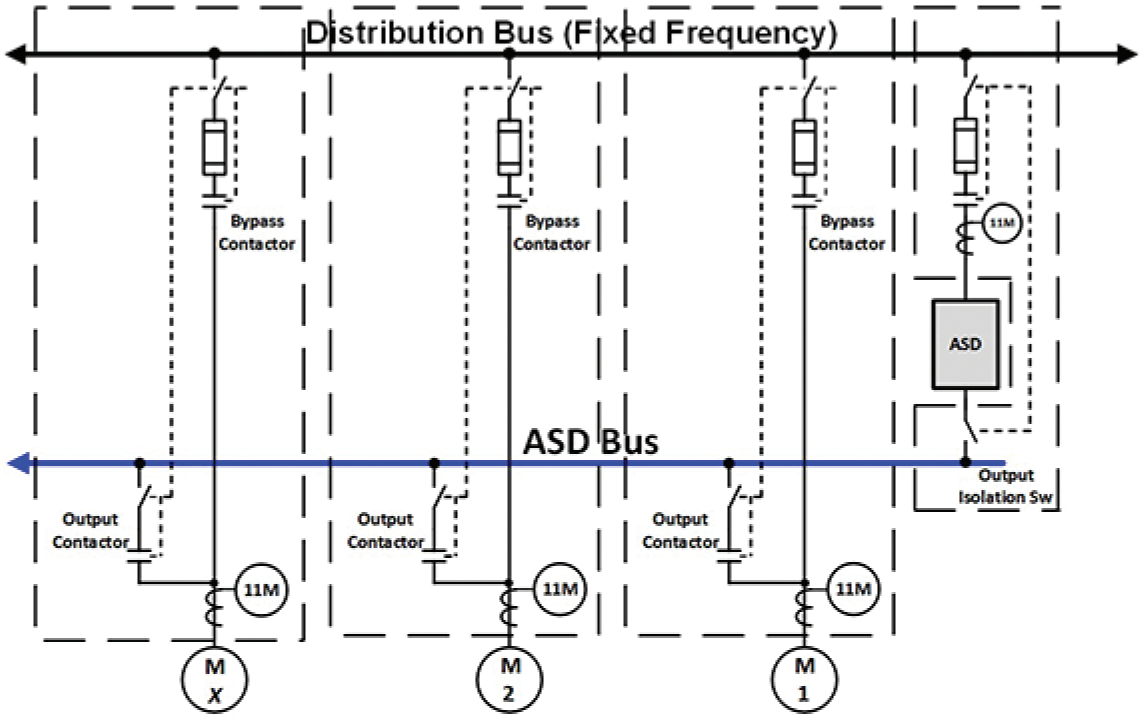
Courtesy of Rockwell Automation.

Figure 52—Typical V/Hz excitation curve of an induction motor

9.3.8 Multiple motor applications

For some ASD applications, the same ASD can be used to start and/or operate multiple motors. The manufacturers of the drive and the motors should provide information for these applications.

The protection for an individual motor is typically online for the motor whether it is connected to the main bus or the ASD starter bus. Reference Figure 53.



Courtesy of Rockwell Automation.

Figure 53—MV multi-motor synchronous transfer system

9.3.9 Shaft voltage and bearing currents and common-mode voltages

In some applications, ASDs have been found to produce currents in bearings of motors they control.

According to IEEE Std 1349-2011, "Shaft voltages occur on all motors whether fed by sine wave power (fixed speed) or by ASD power. Shaft voltages increase for motors on inverter duty due to the common-mode voltage (CMV) imposed by the ASD at the motor terminals. CMV is produced to some extent by all drive topologies since, at any given instant, only two of three phases are conducting as compared to sine wave power where all three phases remain connected to the source. The manner and degree to which this CMV is expressed at the motor terminals is dependent on the specific ASD topology. The resultant magnitude and frequencies of the CMV that may appear at the motor shaft through capacitive coupling will depend on a number of system design factors including ASD carrier frequency, motor geometry, cable type and drive train coupling. The maximum CMV associated with a particular ASD type should be obtained from the ASD manufacturer. Knowing the CMV, the resulting shaft voltage can be calculated from the related motor capacitances. Typically, the shaft voltage will be on the order of 1/10 of the CMV appearing at the motor terminals (Paes, et al. [B49])." Refer to IEEE Std 1349-2011 for a discussion of sparking across bearing lubrication and G.3 in IEEE Std 1349-2011 for CMV calculations for ASD applications showing the amount of energy discharge across the oil film.

In IEEE Std 1349-2011, "The shaft voltage can cause bearing damage because of electrical discharge across the bearings, known as electrical fluting of the bearings. This phenomenon has been considered to be a possible ignition source. To date, measurements of actual voltage and calculations of available energy indicate that this issue should be considered for large motors over 3750 kW (5000 hp), voltages in excess of 6.0 kV, and in conjunction with those instances where the available gas or vapor has a very low minimum ignition energy (MIE) such as hydrogen or acetylene. For example, on a 6500 hp, 6.6 kV, 2-pole motor, measured voltages and calculated capacitances gave a maximum stored energy of 0.2 micro joules, versus an MIE of 280 micro joules

for methane, 18 micro joules for hydrogen, and 17 micro joules for acetylene. Refer to [G.3 in IEEE Std 1349-2011] for example capacitive energy calculations."

In general, the following practices can reduce the detrimental effects of shaft voltages and bearing currents:

— Run the ASD at the lowest carrier frequency that satisfies any audible noise and temperature requirements.
— Insulate both bearings and use dedicated ground path such as a shaft grounding brush on the drive end. Current does not go through the bearing, but is instead conducted directly to ground through the brush. These brushes are specifically selected to tolerate misalignment and maintain rotating contact throughout the brush's life when properly maintained. Insulation for bearings must provide a high impedance to high frequency signals in order to be effective against common-mode voltage–induced bearing currents. See API 541.

CAUTION

Other non-insulated bearings connected to the shaft with a conductive coupling may be damaged by bearing currents.

— Use non-conductive couplings for loads or devices which may be damaged by bearings currents.
— Verify that the control and motor are grounded per the manufacturer's instruction.
— Use a filter that reduces common-mode voltage.

9.3.10 Partial discharge (PD)

PD information and protection is discussed in 8.5.4.6 and Annex C.

10. LV dc motor protection

10.1 General

This clause discusses LV dc motor protection for industrial and commercial applications. It does not include such applications as traction drives (e.g., trains). Refer to IEEE Std 1683 for information on reducing electrical hazards in MCCs up to 1000 V dc. Refer to IEEE Std C37.14™ for dc power circuit breakers.

The purpose of dc motor protection is to reduce motor failure by protecting it from conditions that might damage the windings, whether electrically or mechanically. Winding damage can result from any of the following:

— Contamination
— Excessive moisture
— High dielectric stress
— High temperature

While each of these conditions can cause winding damage, the *most common* failure is thermal degradation (overheating) of the insulation. Insulation life is halved for each 10 °C increase in winding temperature. To avoid thermal degradation of the insulation, there are numerous methods that can be used to monitor potential fault conditions. These devices may be used to alert personnel, and/or to de-energize the motor when these conditions occur.

10.2 Potential failure conditions

A review of motor common failure conditions is useful in understanding the different approaches taken to protect motors. These conditions are divided into the following categories:

— Motor
— Load
— Environment
— Power source
— Application

Motor failure conditions are internal to the motor. These include, but are not limited to, burned insulation, bad bearings, field loss, and those related to the external blower (e.g., blower not operating, operating in the incorrect direction of rotation, or covers not secured). In addition, the same wiring failure conditions that can affect an ac motor can also cause failure of dc motors.

Load failure conditions may either be due to prolonged overloading, or sudden, rapid faults caused when some (usually mechanical) part of the driven load undergoes a mechanical failure. This most often takes the form of jammed parts due to wear, material being processed that is outside the normal condition required for processing, or worn parts. In an extruder or pump application, fluid or material that is cold or highly viscous may cause an overload. Another potential overload example is external equipment, such as a non-functioning heating element meant to warm the pumped fluid to a workable viscosity.

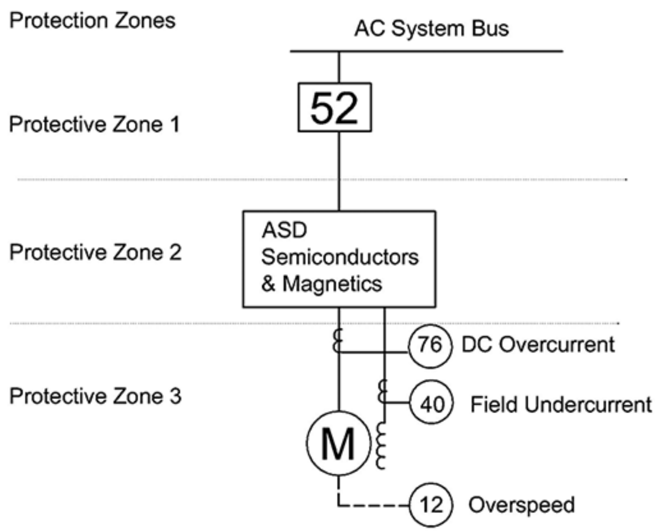
Environmental conditions include high ambient temperature, debris buildup on the exterior (or interior) of the motor, a wet environment, or blocked ventilation. These conditions can cause corrosions of the commutator, inhibiting commutation; reduce the insulation resistance value below specified levels, increase the operating temperature, or otherwise shorten the motor life. It should be recognized that bearing lubricant is often the thermal “weak link” of the motor. Increased operating temperature can shorten the life of bearing lubricant.

Application related failures may result from operating conditions such as rapid cycling or reversing applications, overspeed operation, or loss of fields (resulting in near-instantaneous overspeed).

10.3 LV dc motor protection methods

DC motor protection methods include many of the same functions for electrical, such as overcurrent (Device 76), and mechanical, such as bearing protection (Device 38). In addition, dc motor protection also includes Devices 40, 12, etc. This clause highlights some of the unique protection techniques for dc motor applications. Refer to Figure 54 for a typical protection system for LV dc motor protection.

Thermal overload relays alert the operator of sudden or gradual increases in temperature, which may be caused by blower malfunction as well as overload conditions. These devices may be internal or external. Internal thermal overloads are thermostats (bimetallic elements), embedded in or attached to the motor windings. They are normally affixed to the interpoles, as the interpoles are stationary and subject to the same current as the armature (i.e., load-dependent). These thermostats will open (or close, depending on the designation) at a specific temperature. Thermostats are available in an assortment of temperature-operating points and can be selected to suit the application and insulation class of the motor. They can be affixed to the fields to sense restricted ventilation, ac ripple in the field supply, or overcurrent operation of the fields. The thermostat is normally connected to the control circuitry to de-energize the motor and alert the operator (e.g., sound an alarm, or turn on a warning light). For some applications additional thermostats are installed at lower settings to alarm only.



Courtesy of Schneider Electric.

Figure 54—LV dc motor protection

External thermal overload protection may be heaters connected in series with the armature circuit; they are normally installed directly on the motor contactor. Some of these are single-use (e.g., fuses), while others are resettable. Electronic or magnetic overload protection can also be used. These overloads can be current sensors that sense actual motor current and operate when the current reaches a predetermined level, which then trips a relay to disconnect the motor.

Fuses and circuit breakers are short-circuit protection devices and in some cases can be sized to provide overload protection. The protection, as shown in Figure 54, generally includes the rectifier, power conductors, motor, and the field. Device 52 protects the power circuit and Device 72 protects the field circuit.

Ground fault relays are another type of overcurrent protection detecting a short-circuit between the motor windings and ground. For dc motors, a ground fault is possible in the fields, the armature, or interpoles, as well as the brush rigging and wiring to the motor. DC motors have been known to operate at extremely low insulation resistance values, but doing so is not recommended.

For dc motors, the loss-of-field flux during operation can cause nearly instantaneous acceleration into a dangerous overspeed condition. Within a fraction of a second, the armature and commutator can disintegrate due to very high speeds. The loss-of-field relay, Device 40, is connected in the field circuit and monitors the field current. If the field current is reduced below a preset limit, the Device 40 opens the magnetic contactor of the armature circuit, de-energizing the motor to prevent a runaway speed condition.

When a dc motor stalls, either during acceleration or normal operation, the current-carrying brushes remain in contact with only a few commutator bars. The damage, in this case, is directly to the commutator. The dc motor can be protected from this stall condition by an overcurrent relay set for permissible I^2t times and currents. With large dc motors, another solution is to integrate a zero speed switch into the motor. This switch is often mechanical, with counterweights opposing a spring device. If the zero speed switch does not open, the power supply is de-energized. The switch will also operate when the motor speed decelerates below the preset speed, which may make it less desirable for applications where very low speeds are sometimes required.

10.4 Safety interlocks

Safety interlocks are used to lock out motor contactors. Mechanical interlocks are sometimes used when it is critical that only one of two circuits is energized at the same time (i.e., to prevent a short-circuit condition). There are three types of interlocks:

— Mechanical
— Electrical
— Auxiliary contact

Mechanical interlocks prevent two motor contactors (e.g., forward and reverse) from closing simultaneously. Electrical interlocks incorporate a pushbutton control or auxiliary contact to electrically prevent one contactor from closing while the other contactor is energized. The electrical contactors are either normally closed (NC) or normally open (NO). In a reversing circuit, an NC auxiliary contact is wired in series with the opposing motor contactor coil, and vice versa. Neither contactor can close when the other is energized, thus preventing a direct short-circuit between the two devices.

10.5 Ambient environmental protection

Contamination from the motor operating environment can reduce dc motor life. Dust, abrasive or conductive materials, flammable fumes or liquid, moisture, or corrosive material can contribute to motor failure. Motor enclosures are classified, based upon the level of protection they provide, by the National Electrical Manufacturers Association (NEMA) and the International Electrotechnical Commission (IEC). The two general designations of motor enclosure are open and totally enclosed. While uncommon, dc machines can be constructed to meet the requirements for explosionproof (XP) designation. Even more than ac motors, the dc motor is susceptible to the operating environment, and enclosure construction should be considered when specifying a motor, or evaluating a motor failure.

11. Motor protection for hazardous (Classified) locations

11.1 General

For hazardous (Classified) locations, close coordination with the motor manufacturer is recommended. Information for Class I, Division 2, Class I, Zone 2, and Class II locations is provided below.

CAUTION

For hazardous (Classified) locations, additional caution should be used when selecting and setting motor protection. Refer to the NEC.

Class I, Division 1, Class I, Zone 1, Class I, Zone 0, and Class III locations are beyond the scope of this document.

11.2 Motor protection for Class I, Division 2, and Class I, Zone 2 areas

The motor should be selected to avoid overload conditions. The overload protection requirements are in the NEC, Sections 430.32 (Continuous-Duty Motors), 430.124 (Adjustable Speed Drive overload protection) and 430.225(B) (motors over 600 V nominal). In some locations, similar requirements with some variations may be stipulated by the authority having jurisdiction over the installation. Refer to Padden and Pillai for information on overload types and selection [B48]. Overload conditions affect the typical operating rotor temperatures

shown in IEEE Std 1349-2011. See IEEE Std 1349-2011 for operating temperatures at 1.15 service factor (SF) in TEFC motors.

Sound engineering judgment should be used for setting overload devices considering the motor rating, load, AIT, and operation (NFPA 497-2008 [B47]). For sine wave applications, overload device settings should be 115% or less of motor nameplate rated current for 1.0 SF and 1.15 SF motors. For ASD applications, current setting should be 100% of motor nameplate rated current and overload device settings should be 115% or less of motor nameplate rated current (see IEEE Std 1349-2011).

Auxiliary devices located in Class I, Division 2 or Zone 2 must meet the area classification requirements (Griffith, et al. [B16], IEEE Std 303-2004 [B26]).

11.3 Motor protection for Class II areas

11.3.1 Introduction

There are no additional short-circuit, ground fault, or overload protection requirements given in the National Electrical Code for motors in Class II areas beyond those for motors in ordinary areas. However, motors rated for use in Class II areas need to be operated below the ignition temperatures of the hazardous materials involved. Therefore, care should be taken in selecting the motor starting and control equipment and especially the motor itself when applying motors in Class II areas.

11.3.2 Class II, Division 1 areas

Motors in Class II, Division 1 areas are required to be identified or listed for the location and have a maximum external temperature that is less than the ignition temperature of the specific dust to be encountered. The NEC, 500.8(D)(2), states for motors the abnormal temperature should not exceed 200 °C for Groups E and F and 165 °C for Group G. UL 674 further states that this marking include overload, locked rotor, and single-phasing operation. Consider the following:

a) Internal thermal protection is often needed to comply with the temperature limitations and these temperature controls will need to be wired back to the motor controller in addition to the power wiring. When the thermal protection operates, the motor must stop and cannot be allowed to restart until the thermal protection resets.
b) When dry Group F (e.g., coal) and Group G (e.g., grains and flours) dusts cake on motors and dry out, the ignition temperature can be lowered below the normal ignition temperature of the dust in air.
c) Unless specifically listed by the motor manufacturer, the motor frequency is assumed to be sinusoidal. Use of a solid-state starter (soft start) or an adjustable speed drive can affect the operating temperature of a motor.

11.3.3 Class II, Division 2 areas

A consideration in Class II, Division 2 areas is whether to use general-purpose totally enclosed three-phase induction motors as allowed by Article 502 of the NEC. Consider the following:

NEMA MG 2-2014 recommends that manufacturers be consulted for a number of unusual operating conditions, including the presence of combustible dusts [B43]. Consult with the particular motor supplier being used for the maximum operating temperature of the motor and for the sizes of openings in the motor housing, among other features, to determine if a general-purpose totally enclosed motor is suitable for use in a particular application.

For above NEMA Frame and MV motors in Class II, Division 2 areas, users should work closely with the manufacturer to select appropriate enclosures and cooling method for the specific dusts to be encountered.

Annex A

(informative)

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[18]The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

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Annex B

(informative)

IEEE device designations

B.1 Typical motor protection device function numbers

Table B.1 shows the relationship between IEEE Std C37.2 device function numbers, NEMA designations, and IEC 61850-7-4 [B23] logical nodes. The 1-line and 3-line diagrams showing protective device functions can use the Filled Box method (as illustrated in this standard) or use the List Box method described in C37.2–2008 Figure A.2 and Figure A.3, respectively.

Table B.1—Relationship between IEEE Std C37.2 device function numbers, NEMA designations, and IEC 61850-7-4 logical nodes

Protective function	IEEE device function number	NEMA designation	Modeled in IEC 61850-7-4
Time-delay relay	2	TR	
Multifunction relay	11	—	
Multifunction motor protection relay	11M		
Overspeed device	12	—	
Synchronous-speed check (centrifugal switch), or ac field current	13	FR	
Zero speed and underspeed device	14	—	PZSU
Distance relay (impedance, admittance, or reactance relay)	21	—	PDIS PSCH
Volts per Hz	24		PVPH
Synchronism-check	25		RSYN
Undervoltage, instantaneous, or inverse-time relay	27	UV	PTUV
Directional power/reverse power relay	32	—	PDOP, or PDUP
Undercurrent or underpower relay	37		PTUC PDUP
Bearing protecting device	38	—	
Mechanical condition monitor, vibration	39	—	
Atmospheric condition monitor	45	—	
Reverse phase or phase balance current relay (phase time overcurrent [PTOC] with three-phase information with sequence current as an input or even ratio of negative and positive sequence currents)	46	—	PTOC
Phase sequence voltage relay Negative sequence voltage relay	47	—	PTOV
Motor start-up: Incomplete sequence; Motor starting-time supervision; Motor restart inhibition	48, 51LR 49, 66	—	PMSS PMRI
Thermal overload relay Overload operated by motor current (replica) Rotor thermal overload Stator winding thermal overload (also embedded detectors)	49 49R 49S	OL	PTTR
Overcurrent relay	—	OC	

Table continues

Table B.1—Relationship between IEEE Std C37.2 device function numbers, NEMA designations, and IEC 61850-7-4 logical nodes *(continued)*

Protective function	IEEE device function number	NEMA designation	Modeled in IEC 61850-7-4
Instantaneous overcurrent or rate of rise relay (IOC)	50	—	PIOC
IOC relay, ground	50G	—	
AC time overcurrent relay (TOC) TOC (inverse time) TOC (definite time)	51 51TD	—	PTOC
TOC relay, ground	51G	—	
Extreme overload protection for unloaded start of large synchronous ground motors (usually 750 kW [1000 hp]) set just below pullout torque	51R	—	
Residually connected ground TOC relay	51N	—	
TOC relay, voltage restrained, voltage controlled/dependent	51V		PVOC
Circuit breaker	52	CB	XCBR
Main line contactor	—	M	
Overvoltage relay, instantaneous or time delay (time) overvoltage	59	OV	PTOV
Voltage or current balance relay Over- or undervoltage	60	—	PTOV, PTUV
Breaker failure protection Breaker failure function (with no current monitoring)	50BF or 62BF		RBRF
Time-delay stopping or opening relay	62		
Liquid- or gas-pressure relay or vacuum relay	63	—	
Ground fault detection for current flowing from machine casing or structure to ground (earth fault/ground detection) Rotor earth fault Stator earth fault Inter-turn fault	64 64R 64S 64W	—	PHIZ PTOC PTOC PTOC
Ground fault protective relay	—	GP	
Notching or jogging device (also specified number of successive operations within a given time)	66		
AC directional overcurrent	67		PTOC
Directional earth fault	67G[a]		PTOC, RDIR
Power swing detection/blocking	68		RPSB
Liquid- or gas-level relay	71	—	
DC circuit breaker	72		
Alarm relay	74		
DC overcurrent relay	76		PTOC
AC auto reclosing	79		RREC
Liquid- or gas-flow relay	80	—	
Frequency relay Operated by above (O) normal frequency Operated by below normal frequency (U) Operated by rate of change (R) of supply frequency	81 81O 81U 81R	—	PTOF PTUF PFRC
DC load measuring reclosing	82		
Lockout relay, manually or electrically reset	86	—	

Table continues

Table B.1—Relationship between IEEE Std C37.2 device function numbers, NEMA designations, and IEC 61850-7-4 logical nodes *(continued)*

Protective function	IEEE device function number	NEMA designation	Modeled in IEC 61850-7-4
Differential protective relay, operated by phasor difference between compared electrical quantities Differential bus bar Differential line Motor differential	87 87B 87L 87M	—	PDIF
Restricted earth fault (differential ground fault protection, extra-sensitive detection relay)	87N	—	PDIF
Differential transformer Differential transformer (harmonic restraint) Differential transformer neutral	87T 87TN		PDIF PHAR
Circuit switcher, isolating switch	89		XSWI
Tripping or trip-free relay operates to trip a circuit breaker, contactor, or equipment and prevent immediate reclosure	94	—	
Arc flash detector	AFD		
Non fault disturbance recording digital fault recording	DDR DFR		RDRE (Basic) RADR (Analogue) RBDR (Binary)
Sequence of events recorder	SER		
Trip circuit monitor	TCM		

[a]Per IEEE Std C37.2–2008, 3.5, “The suffix G is preferred where the measured quantity is in the path to ground, or in the case of ground fault detectors, is the current flowing to ground.”

All motors may have some protection functions as described in Table B.1, however, synchronous motors typically have additional protection that is unique to the application. Protection functions for synchronous motors and field excitation systems are shown in Table B.2.

Table B.2—Additional protection functions for synchronous motors and field excitation systems[a]

Protective function	IEEE device function number	NEMA designation	Modeled in IEC 61850-7-4
Synchronous-speed device	13	—	
Loss-of-field/underexcitation protection for synchronous motors	40	FL	PDUP
Field contactor or circuit breaker	41	FC	
Field-discharge resistor	—	—	
Incomplete sequence relay	48	—	
Excitation check relay for synchronous motors	53	—	
Power factor relay (over-, under-power factor)	55	PF	POPF,PUPF
Field application relay	56	—	
Phase angle measuring or out-of-step protective relay	78	—	PPAM

[a]Relationship between IEEE Std C37.2 device function numbers, NEMA designations, and IEC 61850-7-4 logical nodes.

Electronic, solid state, and microprocessor based relays in many cases have security, communication, and other functions as described in Table B.3 below.

Table B.3—Security, communication, and other protection functions[a]

Protective function	IEEE device function number	Comments
Security processing function	16EC or 16SC	Virtual private network (VPN), encryption module, etc.
Firewall	16EF	Or message filtering function
Network managed function	16EM	(e.g., configured via SNMP)
Router	16ER	—
Switch	16ES or 16SS	Example: Ethernet switch is 16ES, dial-up port switch is 16SS
Ethernet managed switch	16ESM	—
Ethernet router, managed, with firewall, VPN for secure communications	16ERFCM	See Annex B, Figure B.2 in IEEE Std C37.2–2008
Serial encrypting modem	16SCT	See Annex B, Figure B.1 in IEEE Std C37.2–2008
Other serial communications components	16ST	Example: 16ST = auto-answer modem or telephone switch
Arc flash detector	AFD	
Clock (or timing source in IEEE Std C37.2)	CLK	Clock
Non-fault-disturbance recording Digital fault recording	DDR DFR	RDRE basic functionality (IEC) RADR analog channel (IEC) RBDR binary channel (IEC)
Environmental data	ENV	
Fault locator		RFLO (IEC)
High impedance fault detector	HIZ	
Historian	HST	
Human machine interface	HMI	
Logic, scheme	LGC	
Substation metering	MET	MMTR, MMXU (IEC)
Phasor data concentrator	PDC	
Phasor measurement unit	PMU	
Power quality monitor	PQM	
Remote input/output device	RIO	
Remote terminal unit	RTU	Also serves as data concentrator
Sequence of events recorder	SER	Time tagged event data
Trip circuit monitor	TCM	

[a]Refer to IEEE Std C37.2–2008 device function numbers.

B.2 Main device letters

The main device letters denote to which the numbered device is applied or is related. The meaning of each single suffix letter, or combination of letters, should be clearly designated in the legend of the drawings or publications applying to the equipment.

A	alarm/auxillary power
AC	alternating current
AN	anode
B	battery/blower/bus

BK	brake
BL	block (valve)
BP	bypass
BT	bus tie
C	capacitor/condenser/compensator/carrier current/case/compressor
CA	cathode
CH	check (valve)
D	discharge (valve)
DC	direct current
E	exciter
F	feeder/field/filament/filter/fan
G	generator or ground[20]
H	heater/housing
L	line/logic
M	motor/metering
MOC	mechanism operated contact[21]
N	neutral/network[22]
P	pump/phase comparisone
R	reactor/rectifier/room/rotor
S	secondary/stator/strainer/sump/suction (valve), synchronizing
T	transformer/thyratron
TC	trip coil
TH	transformer (high-voltage side)
TL	transformer (low-voltage side)
TM	telemeter
TOC	truck-operated contact[23]
TT	transformer (tertiary-voltage side)
U	unit or under

[20]The suffix N is preferred when the device is connected in the residual of a polyphase circuit, is connected across a broken delta, or is internally derived from the polyphase current or voltage quantities. The suffix G is preferred where the measured quantity is in the path to ground, or, in the case of ground fault detectors, is the current flowing to ground. See Figure C.2 in IEEE Std C37.2-2008, for examples.
[21]MOC denotes a circuit breaker mechanism-operated auxiliary switch that is mounted on the stationary housing of a removable circuit breaker.
[22]The suffix N is preferred when the device is connected in the residual of a polyphase circuit, is connected across a broken delta, or is internally derived from the polyphase current or voltage quantities. The suffix G is preferred where the measured quantity is in the path to ground, or, in the case of ground fault detectors, is the current flowing to ground. See Figure C.2 in IEEE Std C37.2-2008, for examples.
[23]TOC denotes a circuit breaker truck-operated auxiliary switch that is mounted on the stationary housing of a removable circuit breaker.

B.3 Other suffix letters

Other suffix letters for protective devices that may typically be used for motor protection schemes are shown below. The meaning of each single suffix letter, or combination of letters, should be clearly designated in the legend of the drawings or publications applying to the equipment.

B	blocking
BF	breaker failure
LR	locked rotor
O	over
PF	power factor
Q	reactive power
T	test/trip/trailing
TC	torque control/thermal capacity
TD	time delay
TDC	time-delay closing contact
TDDO	time delayed relay coil drop-out
TDO	time-delay opening contact
TDPU	time delayed relay coil pickup
THD	total harmonic distortion
U	up/under
V	voltage restrained/voltage controlled
VB	vibration
W	watts
Z	impedance

B.4 Auxiliary devices

These letters denote separate auxiliary devices, such as:

C	closing relay/contactor
CL	auxiliary relay—closed (energized when main device is in closed position)
L	lowering relay
O	opening relay/contactor
OP	auxiliary relay, open (energized when main device is in open position)
PB	push button
R	raising relay
U	“up” position switch relay
V	valve

X	auxiliary relay[24]
Y	auxiliary relay[25]
Z	auxiliary relay

B.5 Auxiliary contact position definitions

- The letters a and b shall be used for all auxiliary, position, and limit switch contacts for such devices and equipment as circuit breakers, contactors, valves and rheostats, and contacts of relays as follows:
- a: Contact that is *open* when the main device is in the standard reference position, commonly referred to as the nonoperated or de-energized position, and that *closes* when the device assumes the opposite position.
- b: Contact that is *closed* when the main device is in the standard reference position, commonly referred to as the nonoperated or de-energized position, and that *opens* when the device assumes the opposite position.

[24]When controlling circuit breakers with an "X-Y" relay control scheme, the X relay is the device whose main contacts are used to energize the closing coil or the device which in some other manner, such as by the release of stored energy, causes the breaker to close. The contacts of the Y relay provide the anti-pump feature for the circuit breaker.

[25]When controlling circuit breakers with an "X-Y" relay control scheme, the X relay is the device whose main contacts are used to energize the closing coil or the device which in some other manner, such as by the release of stored energy, causes the breaker to close. The contacts of the Y relay provide the anti-pump feature for the circuit breaker.

Annex C

(informative)

Motor condition monitors, online

C.1 On-line partial discharge (OLPD) monitoring

C.1.1 Introduction

PD activity can be measured periodically or monitored online continually. The trending of PD over time is used to predict motor-insulation problems, identify motors to be removed from service for repair and maintenance, thereby protecting the motor from catastrophic failure (e.g., winding short-circuit).

While PD monitoring is not in its infancy, this technology is still rapidly developing and the latest technologies should be considered.

C.1.2 PD background

The condition assessment of stator insulation using online partial discharge (OLPD) testing and monitoring has been used for over 50 years. Pioneering developments in Canada/United States (using high-voltage coupling capacitor [HVCC] sensors, resistive temperature detector [RTD] sensors, and stator slot couplers [SSC] sensors) and in the UK/Europe (using both HVCC and air-cored, Rogowski coil [RC] sensors) in the 1960s showed that it was possible to make effective measurements of PD activity in the medium voltage (MV) stator windings of the machines (Stone and Kapler [B59]). Over the past 50 years, the OLPD testing and monitoring of rotating machines has been discussed by many authors as a key tool to understanding the causes of stator insulation failure (Stone and Kapler [B59]). Today, the continuous monitoring of PD activity in rotating machines is an effective method to identify sites of localized damage or degradation ahead of scheduled preventative maintenance outages.

The relevance of OLPD monitoring within rotating machines is discussed by Stone, et al. [B60] and Warren, Stone, and Fenger [B65] as an effective technique to determine the condition of the MV stator winding insulation. The authors used pre-installed 80 pF, HVCC sensors, one or more per phase, to monitor both phase-to-phase and phase-to-earth PD activity within the rotating machine.

Interpretation of the severity of any PD activity has traditionally been carried out by considering the peak PD level (typically given in mV or pC) and also the number of PD pulses across the 50/60 Hz power cycle.

With regards to the application of the OLPD monitoring of MV motors located in Ex/ATEX hazardous gas zones, a recent study by S. Haq, et al. [B18] discussed minimum discharge levels required to produce a possible spark risk. This study was made on rotating machines operating within different gas groups and reports that static charge within the stator winding, if related to surface activity, should be kept below 10 nC for a motor operating in gas group B (hydrogen) to reduce the risk of gas ignition (10 nC equates to a minimum ignition energy of approximately 0.019 mJ). This provides a benchmark, maximum level for static charge in motors exposed to flammable atmospheres, emphasizing the benefit of continuous monitoring of PD activity.

NOTE—PD is not a purely static charge in this sense; it is known that PD activity can lead to active charge surface tracking of 100 nC+ (100 000 pC+) in extreme cases.

C.1.3 PD sensor options

There are a wide range of sensor options available for the online detection of PD activity in motors. These sensors include the slot section coupler (SSC), resistance temperature detector (RTD), high voltage coupling ca-

pacitor (HVCC), high frequency current transformer (HFCT), Rogowski coil (RC), and transient earth voltage (TEV) sensors. The three main types of OLPD sensors used for MV motors (HVCC, HFCT, and RC sensors) are shown below in Figure C.1.

It can be noted from Figure C.1 that at 10 MHz, the HVCC sensor is the most sensitive, followed by the HFCT sensor, and then the RC sensor. The most suitable sensor solution for any application will depend on the motor to be tested and the most suitable point of attachment (POA) for the sensor on the network, either in the motor terminal box or at the switchgear feeder cable enclosure.

 **High voltage coupling capacitor (HVCC)**	 **High frequency current transformer (HFCT)**	 **Rogowski coil (RC) sensors**
80 pF/500 pF/1 nF rating High sensitivity (if installed in the machine's terminal box) "Ex/Atex" certified (for use in hazardous gas zones) The higher the capacitance the better lower frequency response (to sub-10 MHz) Relative sensitivity to an HVCC at 10 MHz = 100%	Available in a range of sizes to fit most confined spaces "Ex/Atex" certified, saturation currents of up to 1000 A High sensitivity ***at low frequencies*** and capable of detecting PD in the machine **remotely at the switchgear** Relative sensitivity to an HVCC at 10 MHz = 30%	Does not saturate with high currents (> 5000 A) "Ex/Atex" certified (for use in hazardous gas zones) Very low sensitivity and thus does not detect low levels of PD, i.e., only significant activity Relative sensitivity to an HVCC at 10 MHz = 1%

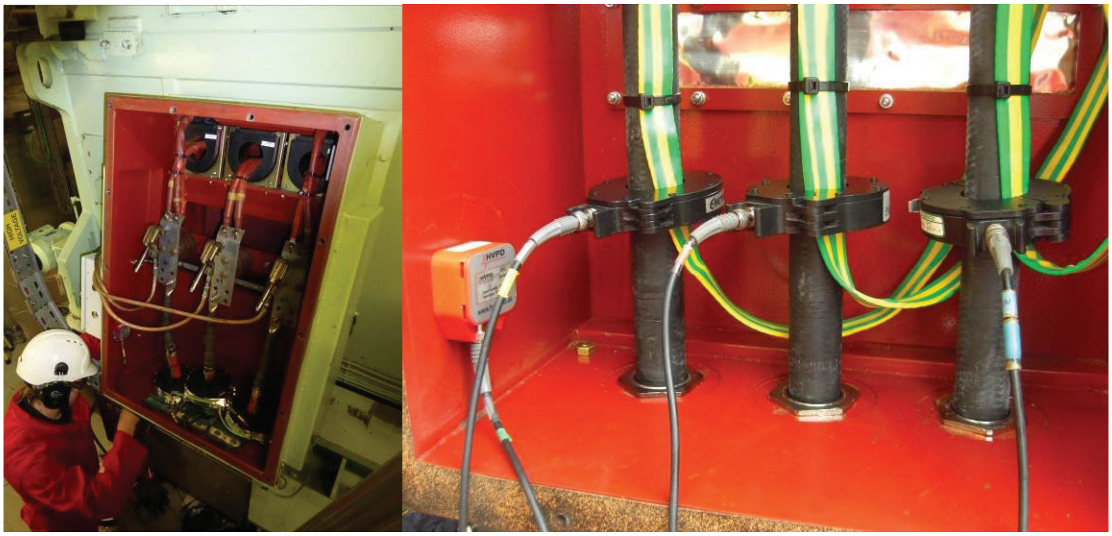
Courtesy of HVPD.

Figure C.1—Three main types of OLPD sensors used for MV motors

While the HVCC sensor is the most widely applied sensor for OLPD monitoring of MV motors, split-core, ferrite HFCT sensors have now been implemented (after over 15 years of industrial application) for the online PD testing of in-service MV cables and motors. The HFCT sensor works inductively to detect PD currents that propagate from the motor winding to the connected power cables. Due to the wideband frequency response of the HFCT sensor (from around 100 kHz to 30 MHz) it is suitable for permanent installation within either the motor terminal box or switchgear cable enclosure at the remote end of the cable as shown in Figure C.2.

C.1.4 HFCT sensor installation

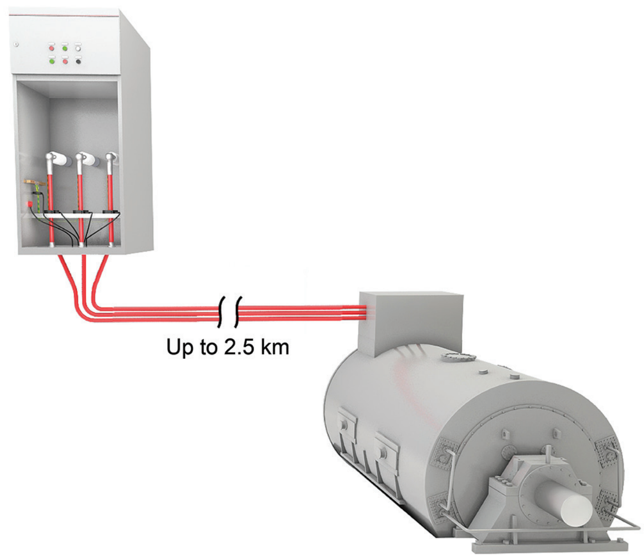
Figure C.2 shows a typical OLPD sensor installation consisting of three HFCT sensors (one per phase mounted on silicon collar supports on the cable tails) and a transient earth voltage (TEV) sensor inside a 10 kV cable enclosure. The photo on the left shows the sensor installation engineer installing the sensors to be used with a permanent monitoring system. The photo on the right shows a temporaty sensor installation to be used during a periodic OLPD test.



Courtesy of HVPD.

Figure C.2—HFCT sensor installation—one per phase (permanent and temporary installation)

The dimensions of the MV power cable are important as they determine the inductance and capacitance per meter (or per foot) of the cable, which effects the distortion of transient PD pulses as they travel along it. For example, polyvinyl chloride (PVC)-insulated cables usually cause the most PD pulse attenuation, followed by paper-insulated lead-covered (PILC) and ethylene propylene rubber (EPR) cables while cross-linked polyethylene (XLPE) cables cause the least attenuation of the traveling pulse. This is related to the different values of relative permittivity of the dielectrics (ε_r) used in the different cable types and the geometry/dimensions of the cable. On-line PD measurements on XLPE cables (in the voltage range 3.3 kV to 15 kV) have been shown to have an effective measurement range for the HFCT sensors of up to 2.5 km/1.5 miles from the motor under test (Renforth, et al. [B52]), as illustrated below in Figure C.3.



Courtesy of HVPD.

Figure C.3—Measurement range for a wideband HFCT sensor connected at the switchgear enclosure for XLPE cables

C.1.5 PD identification and noise mitigation

As discussed in the IEEE and British Standards [B29] and [B9] (in sections 11 and 5 respectively), the risk of misinterpreting PD signals always exists due to interference exhibiting similar characteristics as the PD signals. These IEEE and IEC standards discuss time and frequency domain methods of noise separation, types of interference that can be expected in OLPD testing, and the importance of distinguishing between the origins of the PD activity. The remote monitoring technique developed by the authors has been built on PD classification knowledge rules described in Mackinlay and Walton [B38] and Warren, Stone, and Fenger [B65] that use time and frequency domain parameters to distinguish between PD types and interference. This new, remote PD monitoring technique with HFCT sensors located at the central switchboard can also reduce the risk of adjustable speed drive (ASD) and inverter drive pulses at the machine being classified as noise, as such pulses are attenuated by the low-pass filtering effect of the power cable from the machines under test to the remotely connected OLPD sensors.

C.1.6 Peak PD level and PD activity guidelines

A review of published papers on the measurement and analysis of OLPD severity in MV motors by Renforth, et al. [B52] has shown that the most effective way to measure the severity of any PD activity is to use a combination of three measurements:

a) Peak PD level (Q) measurements (in nC for HFCT).

b) Number of PD pulses (N).

c) PD activity: this is a measure of the cumulative PD activity across the power cycle (measured in nC/cycle for HFCT). Normalized quantity number (NQN) is similar and can also be used.

Table C.1 gives guideline OLPD levels for MV stator winding insulation condition assessment against “Peak PD” levels (in nC—nanocoulombs) and cumulative “PD Activity” (in nC/cycle—nanocoulombs per power cycle) on motors in the 10 kV to 15 kV voltage range. The peak PD level and PD activity guidelines shown

in Table C.1 are based on Renforth, et al. [B53]. While these guideline PD levels provide a good basis for the initial condition assessment of a MV motor's stator insulation, it should be noted that the OLPD condition assessment should not be based on PD magnitude and activity levels alone. It is the trend and variation in the OLPD activity over time which is generally considered as being more important in terms of a diagnostic tool. Therefore, it is also important to closely monitor the trends in both the "Peak PD" level and, more importantly, "PD Activity" over time, using continuous OLPD monitoring systems.

Table C.1—OLPD guideline levels for MV motors in the 10 kV to 15 kV voltage class

Condition assessment	Peak PD level (nC)	OLPD activity (nC/cycle)
Excellent	< 2	< 50
Good	2 to 4	50 to 99
Average	4 to 10	100 to 249
Still acceptable	10 to 15	250 to 499
Inspection recommended	15 to 25	500 to 999
Unreliable	> 25	> 1000

C.2 MV monitoring motor insulation online

Stator insulation degradation is responsible for a large percentage of motor failures. The capacitance (C) and dissipation factor (DF) measurement of motor ground-wall insulation is one of the standard tests to determine the insulation health. In the past the C and DF of the motor insulation could only be determined by off-line testing, meaning that the motor must be taken out of service and tested with portable test equipment. Unfortunately, because motors typically remain in service for many years, the testing interval can be very long (especially in continuous processes) and can be of the same duration as the motor insulation failure. Because no effective mechanism existed to predict insulation failure, this led to unexpected failure of the motor, interruption of the process, and significant repair and downtime costs.

Monitoring motor insulation online using specialized differential current transformers and monitoring equipment can be used to provide an online (while the motor is running and under load) characterization of the motor stator insulation capacitance (C) and the dissipation factor (DF). The specialized differential current transformer enables accurate online measurement of small insulation leakage currents (mA) in the presence of large motor load currents (kA). Using these measurements, both capacitive and resistive components of insulation leakage current can be computed. This provides the user the ability to track the insulation degradation online over the life of the motor and take actions to schedule a repair/replacement at a convenient time, resulting in improved safety, reduced lost production, and reduced unplanned maintenance costs. The data can be collected in a machinery protection or monitoring system, exported to the plant distributed control system (DCS), and other devices for trending. This technology is limited to externally wye connected motors.

Annex D

(informative)

Motor protection examples

Annex D includes some typical examples and protection settings. Each application should be analyzed and the protection devices and settings should be selected for the specific application.

D.1 Typical medium-voltage (MV) motor protection settings

Typical protection settings for MV motor protection devices are shown in Table D.1.

Table D.1—Typical MV motor protection device settings[a]

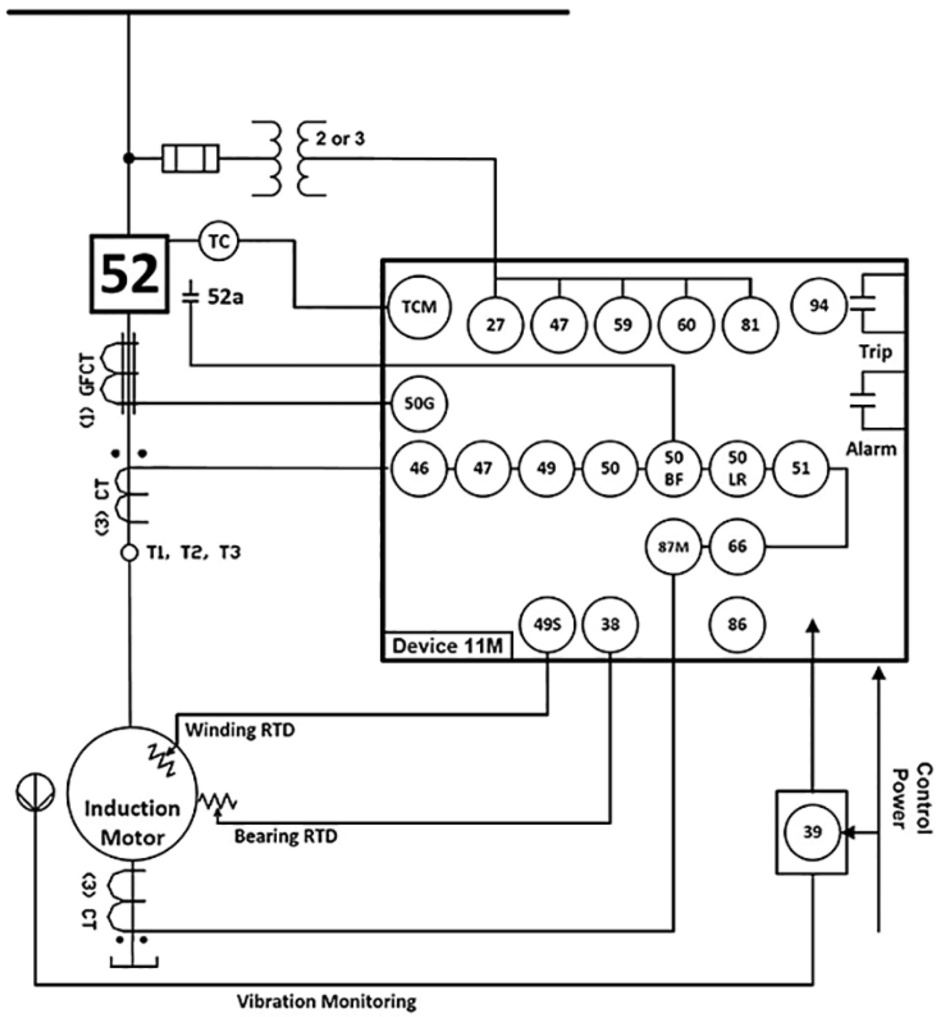
Descriptions	Alarm	Trip
Thermal overload (49)[b]	105%	115% = SF 1.0 125% = SF 1.15
Unbalance voltage (47)	2%	3% to 5%
Unbalance (current) (46) With time overcurrent (TOC) characteristic	10%	15% 10 s time delay
Ground fault (51N) (low resistance grounded systems)		5% to 10% of ground fault current
Ground fault (50G) with zero sequence current transformer (CT) (low resistance grounded systems)		5% to 10% of ground fault current
Ground fault (50G) with zero sequence CT (high resistance grounded systems)		Custom settings set just above the charging current
Undervoltage/overvoltage (27/59) With time delay	± 10% pickup NEMA MG-1 motors are designed to operate at ±10% nameplate voltage	± 15% to 20% pickup
Stator winding temperature (49S)	Above the normal operating temperature; typically about 10 °C below the trip setting	5 °C to 10 °C below the insulation class maximum temperature rating
Bearing temperature (38)	90 °C	100 °C
Bearing temperature (38) (synthetic lubricant)	120 °C	130 °C
Short-circuit (50)		1.6 to 2 times locked rotor (above motor inrush)

[a]Manufacturer's recommendations should be followed for alarm and trip settings. Other settings may be appropriate for emergency and critical service loads.
[b]Reference IEEE Std 1349-2011 for motors located in Class I, Division 2 or Class I, Zone 2 hazardous (Classified) locations with sine wave or ASD power for setting overload devices.

D.2 MV breaker start example

For a MV breaker start example in critical service, refer to Table 6 for the typical motor protection functions, and Figure 18 and Figure 19 for the MV induction motor protection 1-line and 3-line diagrams. Typical settings are in Table D.1.

For a detailed example of a MV induction motor in critical service, the reference example from IEEE Std C37.96–2012, including the motor data sheet, was used. Refer to Table D.2. Figure D.1 is a 1-line diagram for this example as used in this document and uses a motor protection relay, Device 11M, with full differential protection (87M). The settings are for example only and should not be considered recommendations for all applications.



Courtesy of Rockwell Automation.

Figure D.1—Critical service induction motor example, 1-line diagram

Table D.2—MV motor data sheet[a]

1. Buyer's equipment no.		
2. Equipment service FD	**Fan**	
3. Buyer's M/R no.		
4. Horsepower	4423 hp	
5. Service factor (SF)	1.15	
6. Voltage	6600	
7. Phase	3	

Table continues

Table D.2—MV motor data sheet[a] *(continued)*

8. Frequency, hertz	60	
9. Synchronous speed, RPM	900	
10. Full load speed, RPM	895	
11. NEMA design letter	B	
12. Insulation class	F	
13. Temperature rise, °C (by resistance) at full load	68	
14. Full load current, amps	349.6	
15. Locked rotor current, amps	2202 (FL × 6.3)	
16. Locked rotor torque, % full load	80	
17. Breakdown torque, % full load	200	
18. Efficiency	100% load	96
	75% load	96
	50% load	95.8
19. Power factor	100% load	0.86
	75% load	0.84
	50% load	0.77
20. Enclosure[b]	WPII	
21. Mounting	Foot	
22. Rotation[c]	CCW (viewed from non-drive end)	
23. Bearing type	Sleeve	
24. Frame no.	10409	
25. Manufacturer	WEG	
26. Serial no.	TBA	
27. Space heater	350 W	120 V
28. O/A dimension Drawing Number	9303.8	
29. Weight	31 050 lb	
30. Terminal box L × W × H, in.		
31. Load WK2, lb. ft^2	38277	
32. Rotor WK2, lb. ft^2	8433	
33. Starting motor PF		
34. Open circuit time constant, seconds	Obtain data from manufacturer	(See Annex E)
35. Short-circuit time constant, seconds	Obtain data from manufacturer	
36. Subtransient reactance and X/R	13.9	
37. Running cooling time constant, minutes	75	
38. Stopped cooling time constant, minutes	441	
39. Code letter	G	
40. Resistance temperature detector (RTD) alarm temp. (windings)	130 °C	
41. RTD trip temp. (windings)	155 °C	
42. Running cooling time, minutes	225	This equals 3 time constants (3 × line 37)
43. Stopped cooling time, minutes	1323	This equals 3 time constants (3 × line 38)
44. Number of starts, hot[d]	2	
45. Number of starts, cold[d]	3	

Table continues

Table D.2—MV motor data sheet[a] *(continued)*

46. Terminal box location (viewed from drive end)	Left	
47. Hot safe stall time	19	
48. Cold safe stall time	23	

[a]Table D.2 is reprinted with permission from IEEE Std C37.96–2012, Table A.1.
[b]Enclosure: WP II (weather protected, Type II).
[c]Viewed from end opposite coupling.
[d]Include minimum time at standstill and the minimum time running before an additional start.

The induction motor is protected by a multifunction relay GE Multilin type 869. Some protection settings are based on IEEE Std C37.96–2012 and information contained in this document. Short-circuit, power flow, motor starting, arc flash, and other studies are usually required to set protective devices. Refer to Figure D.3 for relay Device 11M model and relay properties, CT ratio and characteristics, and VT ratio and characteristics.

Table D.3—Relay Device 11M, CT and VT properties

Manufacturer	Model	Control voltage			
GE Multilin	869	120 V ac 60 Hz UPS			
Phase CTsa line side ratio/class	**CT withstand**	**CT resistance**	**Phase CTs[a, b] neutral side ratio/class**	**CT withstand**	**CT resistance**
400:5 C100	1 × @ 30 °C 0.6 × @ 55 °C Continuous	1.279 Ohms @ 75 °C	400:5 C100	1 × @ 30 °C 0.6 × @ 55 °C Continuous	1.279 Ohms @ 75 °C
Ground CTs[c] line side ratio/class	**CT withstand**	**CT resistance**			
50:5 C100	1 × @ 30 °C 0.6 × @ 55 °C continuous	1.279 Ohms @ 75 °C			

[a]Phase CTs on the load side and phase CTs on the neutral side should be the same model and ratio for differential (87M) relaying. CTs should be shipped to the motor manufacturer for installation or field installed as needed. (Confirm CT ratio and model number). Refer to Figure D.1.
[b]Neutral ground sensing is a residual connection from the neutral-side phase CTs. Refer to Figure D.1.
[c]Ground Zero sequence CTs should be relay class CTs.

See Table D.4 for recommended settings for this particular example.

See Table D.5 for typical inputs to Device 11M to trip the breaker and block motor start for this particular example.

See Table D.6 for typical output relays from Device 11M to send alarm, trip, and transfer trip signals for this particular example.

The time current characteristic curves for phase faults are shown in Figure D.2.

Table D.4—Device 11M protection settings

Function number	Description (relay name)	Program setting	Primary value	Secondary value	Output relay	Comments
27	Undervoltage alarm (Phase UV 1)	Pickup: 0.86 × VT Pickup delay: definite time 3 s	5940 V	103 V	ALARM	AUX RY4: Any alarm Alarm will be chosen at about 90% × rated nameplate of motor for alarm with definite time delay set at 3 s.
27	Undervoltage trip (Phase UV 2)	Pickup: 0.81 × VT Pickup delay: inverse time D = 1 curve	5610 V Sample points on the inverse curve 50% pickup ~2 s 80% pickup ~5 s	97.6 V	TRIP	AUX RY1: Trips breaker The trip is set at 85% × rated nameplate of motor with inverse time curve set at D = 1 (1 s at 0% voltage pick-up). Undervoltage setting depends on stiffness of the power system, motor bus transfer, load shed schemes, etc. Relay setting: Alarm = 0.90 × 6600 V/6900 = 0.86 Trip = 0.85 × 6600 V/6900 = 0.81 Measured values: Alarm = 0.90 × 6600 V × (120/6900) = 103 V Trip = 0.85 × 6600 V × (120/6900) = 97.6 V Notes: —In GE 869 motor protection relay, pickup is set multiple of base voltage (VT). In this case, the base voltage equals 6900 V at primary or 120 V at secondary of voltage transformer. —Undervoltage function may also be used to block starting of the motor. —Consider using a time delay block start following power outages.

Table continues

Table D.4—Device 11M protection settings *(continued)*

Function number	Description (relay name)	Program setting	Primary value	Secondary value	Output relay	Comments
59	Overvoltage alarm (Phase OV)	Pickup: 1.05 × VT Pickup delay: definite time 3.0 s	7260 V	126 V	ALARM	AUX RY4: Any alarm Alarm will be chosen at about 110% × rated nameplate of motor for alarm with definite time delay set at 3 s. AUX RY1: Trips breaker The trip is set at 115% × rated nameplate of motor for alarm with definite time delay set at 0.5 s. Overvoltage setting depends on overexcitation characteristics of the motor; where this data should be given by the motor manufacturer. Relay setting: Alarm = 1.10 × 6600 V/6900 = 1.05 Trip = 1.15 × 6600 V/6900 = 1.10 Measured values: Alarm = 1.10 × 6600 V × (120/6900) = 126 V Trip = 1.15 × 6600 V × (120/6900) = 132 V Notes: —In 869 motor protection relay, pickup is set multiple of base voltage (VT). In this case, the base voltage equals 6900 V at primary or 120 V at secondary of voltage transformer. —In IEEE Std C37.96–2012, this protection is typically disabled since moderate steady state overvoltage is not generally an issue.
59	Overvoltage trip (Phase OV)	Pickup: 1.10 × VT Pickup delay: definite time 0.5 s	7590 V	132 V	TRIP	
37	Undercurrent alarm	Start block delay: 10 s 0.7 × full load current (FLC) Definite time: 5 s			ALARM	AUX RY4: Any alarm Alarm settings may need to be load adjusted in the shop/field. FLC is FLA in the 869 relay.
37	Undercurrent trip	Start block delay: 10 s 0.5 × FLC Definite time: 10 s			TRIP	AUX RY1: Trips breaker Trip settings may need to be load adjusted in the shop/field. FLC is FLA in the 869 relay.

Table continues

Table D.4—Device 11M protection settings *(continued)*

Function number	Description (relay name)	Program setting	Primary value	Secondary value	Output relay	Comments
38	Bearing temperature alarm (RTD alarm)	Temperature: 90 °C Pickup delay: 3 s			ALARM	AUX RY4: Any alarm AUX RY1: Trip AUX RY11: 86-LOR1 Locks out motor breaker Bearing temperatures should be set with an alarm of 90 °C and trip at 95 °C (unless lower temperature values are indicated in the motor data sheet or outline diagram).
38	Bearing temperature trip (RDT trip)	Temperature: 95 °C Pickup delay: 5 s			TRIP 86 LOR1	
46	Phase current balance alarm (current unbalance)	Pickup: 10% Pickup delay: 10 s			ALARM	AUX RY4: Any alarm The alarm level will be set at 10% of FLC with time delay of 10 s. FLC is FLA in the 869 relay.
46	Phase current balance trip (current unbalance)	Pickup: 15% Pickup delay: 10 s			TRIP	AUX RY1: Trips breaker The trip level will be at 15% of FLC with time delay of 10 s. This setting should avoid nuisance tripping on small voltage imbalances. FLC is FLA in the 869 relay.
47	Phase sequence voltage relay trip (phase reversal)	Pickup delay: 5 s			TRIP	AUX RY1: Trip When phase-to-phase voltages (Vab, Vbc, and Vca) are greater than 50% of VT, if the phase rotation of the three phase voltages is not same as the programmed phase rotation and there is no fuse failure, either an alarm or a trip and a start inhibit will occur within programmed pickup delay time.
47	Negative sequence trip (negative sequence OV1)	0.047 × VT Pickup delay: 10 s	324 V (negative sequence)	5.64 V (negative sequence)	TRIP	AUX RY1: Trips breaker Detect asymmetrical system voltage conditions. Loss of 1 phase or 2 phases or reversed phase sequence. A 5% voltage unbalance results in about 20% to 25% current unbalance. 6600 V × 0.05 = 330 V 330 ÷ 6900 = 0.047
46	Negative sequence Overcurrent trip (negative sequence IOC1)	Pickup: 0.175 × CT Pickup delay: 5 s	70 A (negative sequence)	0.875 A (negative sequence)	TRIP	AUX RY1: Trips breaker Used to detect clear unbalance in the system, i.e., heavy load; CTs; 3-phase faults; fault inception; switch off during 3 phase faults. FLC × 20% = 349.6 × 0.20 = 69.92 A 69.92 ÷ 400 = 0.175

Table continues

Table D.4—Device 11M protection settings *(continued)*

Function number	Description (relay name)	Program setting	Primary value	Secondary value	Output relay	Comments
49	Thermal overload, motor current (replica) alarm (thermal model)	Alarm pickup: 75% of thermal capacity			ALARM	AUX RY4: Any alarm AUX RY1: Trips breaker Notes: —The standard overload curves will be selected to match the motor thermal limit curves for hot running overload. This approach will protect the motor under overload and starting conditions. —Do not choose a very conservative curve. —A custom curve may have to be developed in the relay depending on the available standard overload curves in the relay and if there is less margin between the motor thermal and accelerating limit curves. —Optional settings for the thermal capacity calculations include: unbalance bias K factor; RTD bias; and voltage dependent.
49	Thermal overload, motor current (replica) trip (thermal model)	Overload curve: motor TD multiplier: 6 Cool time constant running: 75 min Cool time constant stopped: 441 min Hot/cold safe stall ratio: 0.82			TRIP	
49S	Stator winding temperature alarm RTDs 1 through 6 Stator temperature alarm (RTD temperature alarm)	Alarm temperature: 130 °C 2 s			ALARM	AUX RY4: Any alarm Set above the normal operating temperature; typically about 10 °C below the trip setting.
49S	Stator winding temperature alarm RTDs 1 through 6 Stator temperature trip (RTD temperature trip)	Trip temperature: 155 °C 2 s			TRIP	AUX RY1: Trips breaker Set 5 °C to 10 °C below the insulation class maximum temperature rating. This setting depends on motor temperature rise design. If a motor is designed for Class B temperature rise with Class F insulation, which is a normal case, trip setting would be 145 °C to 150 °C. RTD Voting can reduce nuisance tripping.
50BF	Breaker failure trip (breaker failure)	0.1 × CT 300 ms	40 A	0.5 A	TRIP Transfer trip 86 LOR1	AUX RY1: Trips breaker AUX RY16: Transfer trip other source breakers AUX RY11: 86-LOR1 locks out motor breaker The time delay may be different for motor bus. Transfer applications and other considerations.

Table continues

Table D.4—Device 11M protection settings *(continued)*

Function number	Description (relay name)	Program setting	Primary value	Secondary value	Output relay	Comments
50G	Ground overcurrent trip (line side) (ground instantaneous overcurrent protection)	Pickup: 0.4 × CT Pickup delay: 0.2 s	20 A	2 A	TRIP 86 LOR1	AUX RY1: Trips breaker AUX RY11:86-LOR1, locks out motor breaker As shown in Figure 18, motor feeder has zero sequence CT with a ratio of 50/5 A, which will provide independent ground source signal to motor protection relay. The neutral ground overcurrent will be set at 20 A with a time delay of 0.2 s to avoid any spurious tripping during motor starting. These setting need to be coordinated with upstream device ground fault settings.
50LR	Instantaneous overcurrent-locked rotor (delay on start) (mechanical jam)	Pickup: 1.75 × CT Pickup delay: 1 s delay	700 A	8.75 A	TRIP 86 LOR1	AUX RY1: Trips breaker AUX RY11:86-LOR1, Locks out motor breaker This will be set to two times the FLC with a time delay setting of 1 s, this will be 2 × 349.6 A = 699.2 A, which will be 1.75 times CT primary. Note: Function is also blocked during start-up.
50P	Phase instantaneous overcurrent (phase instantaneous overcurrent)	Pickup: 11 × CT	4400 A	55 A	TRIP 86 LOR1	AUX RY1: Trips breaker AUX RY11:86-LOR1, Locks out motor breaker. This will be set to two times the LRC with no intentional time delay, this will be 2 × 2202 A = 4404 A, which will be 11.0 times CT primary. Notes: —If the protective device effectively removes the dc offset from the current signal, the pickup can be set more sensitively (around 1.25 times the LRC). —This device typically protects the motor branch circuit conductor and it should be sized accordingly for short-circuit protection.
51	Phase overcurrent alarm (phase time overcurrent TOC1)	0.88 × CT Definite time TDM 7 s	352 A	4.4 A	ALARM	AUX RY4: Any alarm Any current over rated nameplate is considered overloaded. Operators should consider corrective action to reduce motor current. 1.01 × 349.6 A = 353 A

Table continues

Table D.4—Device 11M protection settings *(continued)*

Function number	Description (relay name)	Program setting	Primary value	Secondary value	Output relay	Comments
51	Phase overcurrent trip (phase time over-current TOC2)	Pickup: 1.09 × CT Inverse curve or flexcurve	436A	5.45 A	TRIP 86 LOR1	AUX RY1: Trips breaker AUX RY11:86-LOR1, locks out motor breaker Maximum trip setting for 1.15 SF motor is 125% FLC. 1.25 × 349.6 A = 437 A Notes: —Proper time-current characteristics (curve) will be set for coordination with motor-starting characteristics and thermal limits. —This device typically protects the motor branch circuit conductor and it should be sized accordingly.
60FL	VT fuse failure alarm (VT fuse failure, VTFF)				ALARM WARNING Block 27	AUX RY4: Any alarm AUX RY9: Warns operator to shutdown motor and Block Device 27, etc.
66	Number of starts Jogging protection (maximum starting rate)	Interval: 60 min Maximum number of starts: 2 (or 3 if cold start)			Blocks Start/ blocks Breaker close	The thermal inhibit feature in the GE 869 relay confirms that adequate thermal capacity is available in the motor before restart permissive is issued, but jogging block function will be used as backup protection. The maximum number of starts per hour or minimum time between starts (typically available from the manufacturer's data) can be entered directly in the relay to protect the motor from excessive heating due to starting too frequently.
TCM	Trip circuit monitor alarm (trip coil monitor)	Breaker status closed 52 open/closed			ALARM WARNING	AUX RY4: Any alarm AUX RY9: Warns operator to shutdown motor
81U	Underfrequency alarm (underfrequency 1)	Pickup: 59 Hz Pickup delay: 10 s			ALARM	AUX RY4: Any alarm
81U	Underfrequency trip (underfrequency 2)	Pickup: 57.9 Hz Pickup delay: 15 s			TRIP	AUX RY1: Trips breaker NEMA MG-1 has underfrequency limit of 5%
	Underfrequency trip (underfrequency 2)	Pickup: 57.5 Hz Pickup delay: 2 s			TRIP	

Table continues

Table D.4—Device 11M protection settings *(continued)*

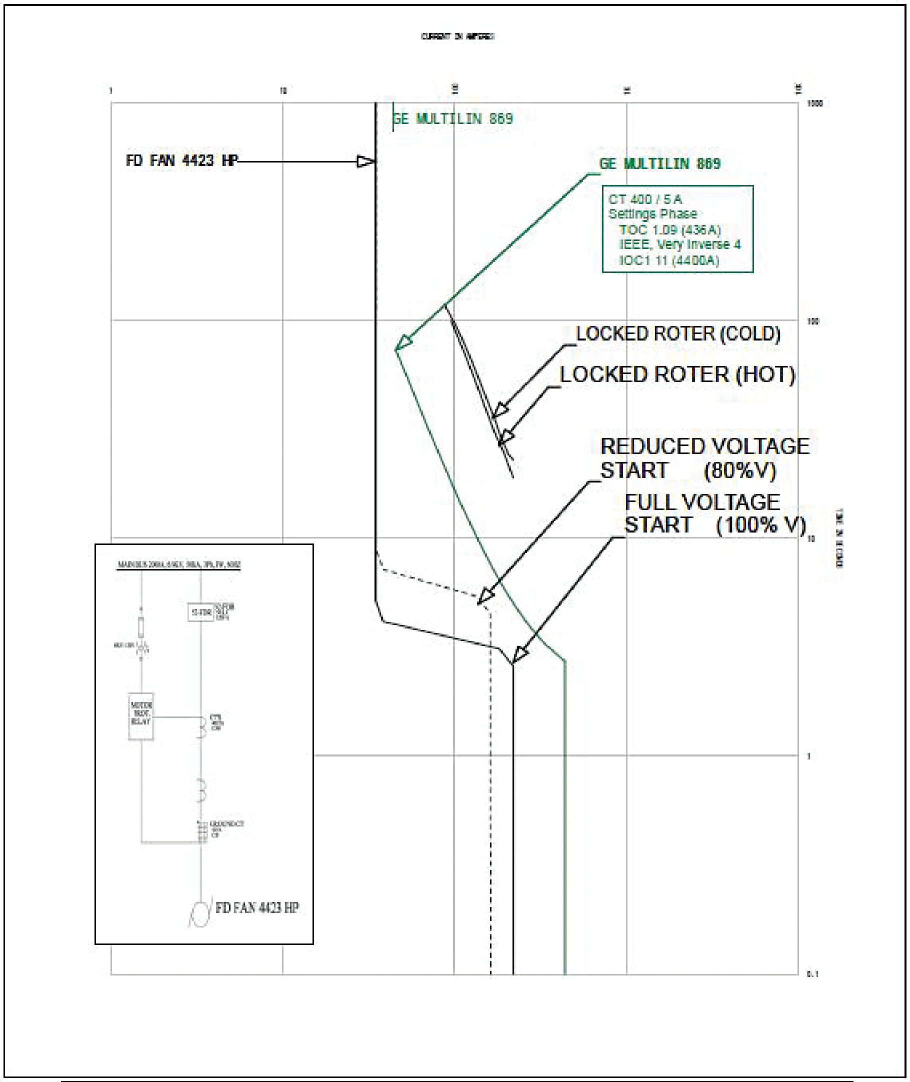
Function number	Description (relay name)	Program setting	Primary value	Secondary value	Output relay	Comments
81O	Overfrequency alarm (overfrequency 1)	Pickup: 60.6 Hz Pickup delay: 10 s			ALARM	AUX RY4: Any alarm
81O	Overfrequency trip (overfrequency 2)	Pickup: 61 Hz Pickup delay: 15 s			TRIP	AUX RY1: Trips breaker NEMA MG-1 has overfrequency limit of 5%
	Overfrequency trip (overfrequency 3)	Pickup: 61.5 Hz Pickup delay: 2 s			TRIP	
86	Breaker lockout				TRIP	AUX RY1: Trips breaker AUX RY10:86-LOR1, locks out motor breaker
87M	Phase differential (percent differential)	Internal sum pickup: 0.1 × CT Slope 1: 10% Break 1: 1.5 × CT Break 2: 4 × CT Slope 2: 95% Pickup delay: 0.10 s Restraint factor starting: 0.000 Block: off Relay: 10 Events: Enabled Targets: Latched	40 A	0.5 A	TRIP 86 LOR1	AUX RY1: Trips breaker AUX RY11:86-LOR1, locks out motor breaker Conventional phase differential (Refer to Figure D.1) Notes: —Differential settings should allow for CT error and differences in CT characteristics. —This relay setting starts at 10% slope for 0.1 × CT pickup to 1.5 × CT; then 95% slope from 1.5 × CT to 4 × CT; then 10% slope above 4 × CT.
AFD	Arc flash detector					Consider for each application

Table D.5—Device 11M input devices and settings

Function number	Description	Program setting	Input to 11M relay	Comments
52_a 52_b	Breaker open/closed auxiliary contacts status	Bounce 10 ms enabled	Contact input 1 Contact input 2	Input to 11M: terminal block F: Normally open 52a: terminals F13 and F21 Normally closed 52a: terminals F14 and F21
OPEN	Open breaker	Bounce 10 ms enabled	Contact input 3	Input to 11M: terminal block F: terminals F15 and F21
CLOSE	Close breaker	Bounce 10 ms enabled	Contact input 4	Input to 11M: terminal block F: terminals F16 and F21
39	Vibration protection alarm	Bounce 10 ms enabled	Contact input 5 dry contact	Input to 11M: terminal block F: terminal 17 and 21 (normal-closed contact; vibration-opens contact) 11M output AUX RY4: Any alarm Notes: —Analog signals may be sent from some devices for tracking
39	Vibration protection trip	Bounce 10 ms enabled	Contact input 6 dry contact	Input to 11M: terminal block A: Terminal 18 and 21 (normal-closed contact; vibration-opens contact) 11M output TRIP: trips breaker 11M output Relay11: 86-locks out motor breaker Notes: —Analog signals may be sent from some devices for tracking/trip
ESD	Emergency shutdown trip (input) (switching device control)	Bounce 10 ms enabled	Contact input 7 dry contact	Input to 11M; terminal block F: terminal 19 and 21 (normal-closed contact; ESD-opens contact) 11M output TRIP: trips breaker 11M output relay11: 86-locks out motor breaker trips breaker and shuts off the motor during plant emergency shutdown
49S	RTDs stator RTD 1 to RTD 6	Alarm: 130 °C Trip: 155 °C 5 s	RTD inputs B1-B18	AUX RY4: any alarm 11M output TRIP: trips breaker (Also see 49S settings in Table D.4)
38	RTDs bearings RTD 7 and RTD 8	Alarm: 90 °C Trip: 95 °C 5 s	RTD inputs C1-C18	AUX RY4: Any alarm 11M output TRIP: trips breaker (Also see 38 settings in Table D.4)

Table D.6—Device 11M output signals and settings

Output relay	Description	Program setting	Output of 11M	Comments
TRIP	Trips motor breaker	Contacts close to trip Any trip; Self-reset; Non-failsafe	Output Relay 1: TRIP	Output from 11M: Terminals F1 and F2 Trips breaker, stops motor
CLOSE	Closes motor breaker	Contacts close to start motor Block-relay 16: 86 lock out Contact input 4 (close) Self-reset; Non-failsafe	Output Relay 2: CLOSE	Output from 11M: Terminals F4 and F5 Closes breaker, starts motor
START INHIBIT	Blocks motor start and breaker close	Pre-programmed for blocking motor restart on thermal capacity Normally closed contact Non-failsafe Opens to block motor start	Output Relay 3: START INHIBIT	11M: Terminals F7 and F8 Jumper F7 to F4 F8 is + voltage for close circuit 11M output START INHIBIT: Blocks motor start and prevents breaker close
ALARM	Any alarm	Opens to alarm Any alarm Latched; Non-failsafe	Output Relay 4: ALARM	Output from 11M: Terminals F10 and F11 Sends alarm to operator
CRITICAL FAILURE RELAY	Relay failure	Pre-programmed for warning operator of relay failure Opens to alarm; Non-failsafe	Output Relay 8: CRITICAL FAILURE RELAY	Output from 11M: Terminals F22 and F23 Sends alarm to operator of critical relay failure and warns operator to shutdown motor
WARNING	Warns operator to shutdown motor	Opens for warning Self-reset; Non-failsafe	Output Relay 9: WARNING	Output from 11M: Terminals G1 and G2 Sends warning to operator to shutdown motor
86 LOCK OUT	LOCK OUT RELAY 86-LOR1	86 lock-out relay Blocks motor from starting; Blocks breaker close Closes to energize 86 LO relay Latched; Non-failsafe	Output Relay 11: 86 lock out relay	Output from 11M: Terminals G8 and G9 Energizes 86 lock-out relay (internal and/or external) Blocks motor from starting and blocks breaker close
50BF	50 BF breaker failure	Transfer trip upstream breaker Closes to trip Breaker fail 1 52B Superv OP Latched Blocks breaker close Seal-in time: 0.10 s Pulsed; Non-failsafe	Output Relay 16: 52B Breaker fail	Output from 11M: Terminals G23 and G24 Transfer trips upstream breaker

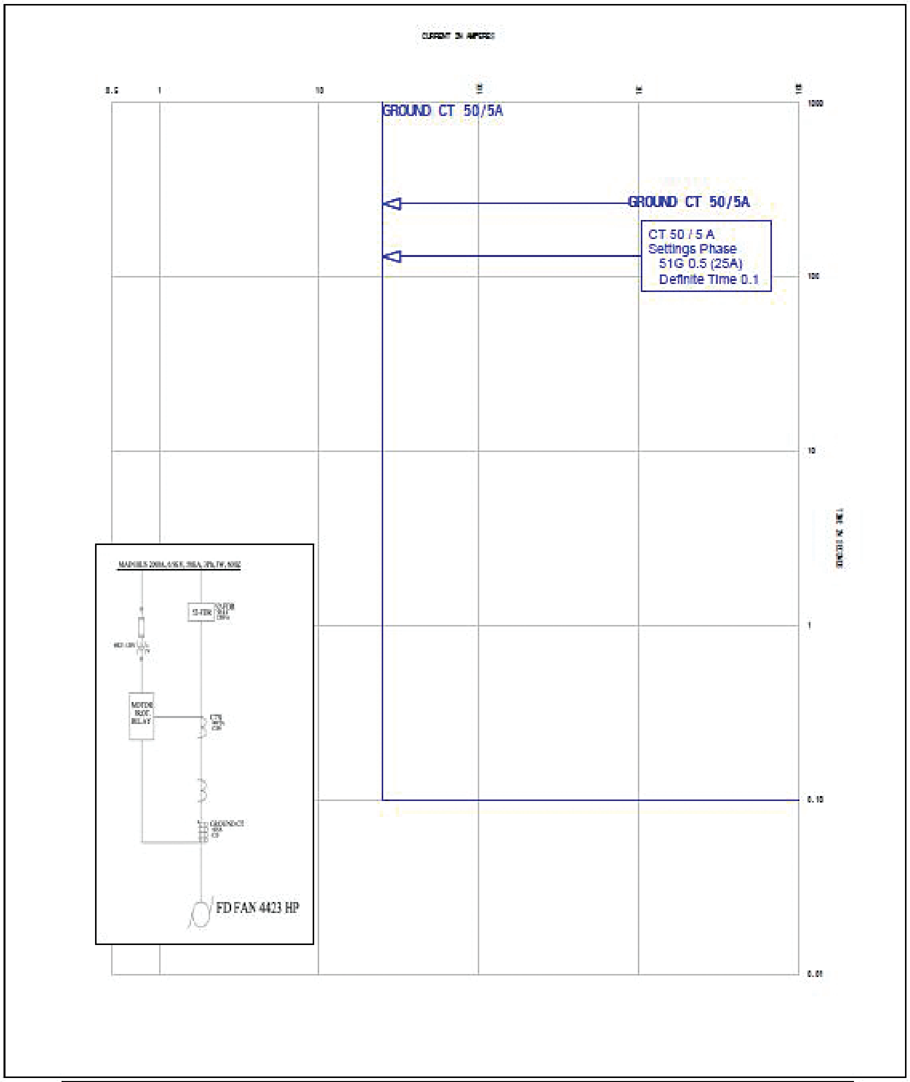


TCC Name: IEEE 37.96-2012 A.3 EXAMPL Current Scale x 10 Reference Voltage: 6900
Oneline: FIG A.5 MOTOR DATA TABLE A.1 RELAY SETTING TABLE A.2
PHASE

Courtesy of DC Water.

Figure D.2—MV example time current characteristic curve plot, phase faults

The time current characteristic curves for ground faults are shown in Figure D.3.

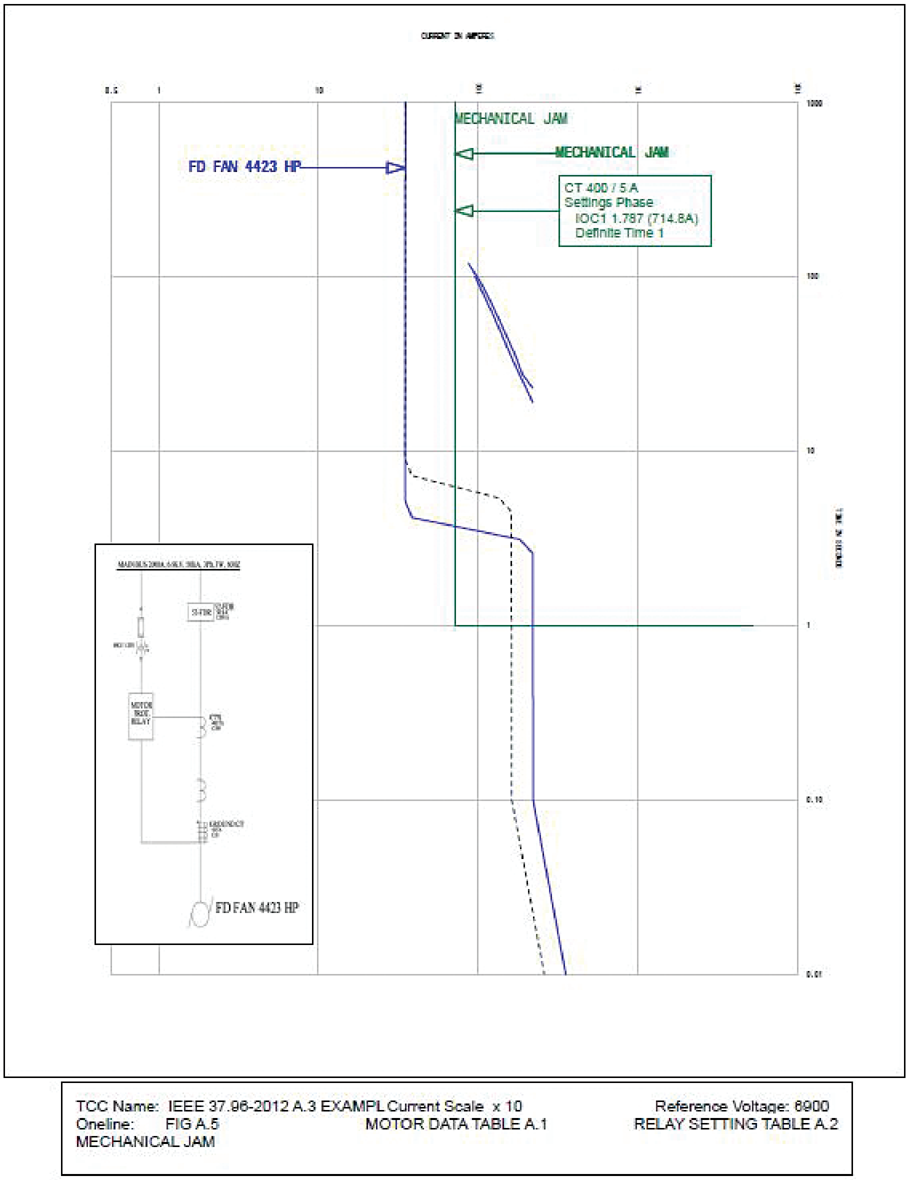


TCC Name: IEEE 37.96-2012 A.3 EXAMPLECurrent Scale x 1 Reference Voltage: 6900
Oneline: FIG A.5 MOTOR DATA TABLE A.1 RELAY SETTING TABLE A.2
GROUND

Courtesy of DC Water.

Figure D.3—MV example time current characteristic curve plot, ground faults

The time current characteristic curves for the locked rotor function is shown in Figure D.4. This function is time delayed on start.



Courtesy of DC Water.

Figure D.4—MV example time current characteristic curve plot, locked rotor function

Annex E

(informative)

Motor open circuit time constant

Annex E includes an example of a motor open circuit time constant, with and without fixed capacitors. Fixed capacitor will extend motor open circuit time constant and will increase the minimum time for blocking the motor starting to allow for motor residual voltage to reach an acceptable level. Contact the motor manufacturer for the motor equivalent circuit data with and without the fixed capacitor.

Using the motor equivalent circuit (Figure E.1) values, we can calculate the open circuit time constant. The formula for this is Equation (E.1):

$$c = \left(\frac{X_m + X_2}{2\pi f r_2} \right) \tag{E.1}$$

where

X_m is magnetizing reactance
X_2 is rotor leakage reactance per phase at rated speed
f is line power frequency
r_2 is rotor resistance per phase at rated speed
c is open circuit time constant

Where c is the open circuit time constant, the voltage of the decay at any time t can be calculated by Equation (E.2):

$$V(\mathrm{t}) = \frac{1}{e^{t/c}} \times V \tag{E.2}$$

where

V is voltage at start time, t = 0
$V(t)$ is voltage of the decay at any time, t
t is time in seconds

When $t = c$, the voltage will be 36.8% of the rated voltage since the base of the natural log (e) is 2.718 and 1/2.718 = 0.368. Therefore, c is one open circuit time constant in seconds (ANSI/EASA AR100–2015 [B2]).

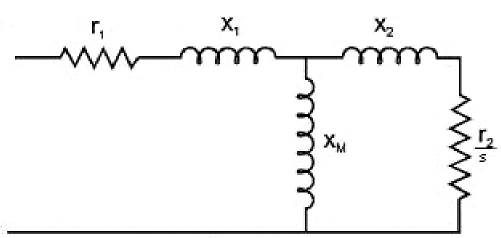


Figure E.1—Typical motor equivalent circuit

The values for the equivalent circuit are available from the motor manufacturer. They cannot be measured or calculated without specific information about the motor's design. For a particular 75 horsepower motor, the values are:

$X_m = 30.74\ \Omega$

$X_2 = 0.309\ \Omega$

$f = 60$ Hz

$r_2 = 0.258\ \Omega$

Substituting these values in the open circuit time constant from Equation (E.1), results are shown in Equation (E.3):

$$c = \left(\frac{30.74 + 0.309}{2\pi(60 \times 0.258)} \right) = 0.319 \tag{E.3}$$

As before, if $t = c$, the voltage at the motor terminals will be 36.8% of the applied voltage. If the applied voltage is 480 V and $t = 0.319$ s, we can show this by Equation (E.4):

$$V(t) = \frac{1}{e^{0.319/0.319}} \times 480 = 177\ \mathrm{V} \tag{E.4}$$

The residual voltage transfer method is not a synchronous method as it only closes at low bus voltage and ignores the phase angle and slip frequency between the motor bus and the new source. The residual voltage transfer method exposes motors to a 50% probability that the close angle at transfer will exceed the 90° maximum phase angle specified by ANSI/NEMA Std C50.41–2012 [B3]. Field results indicate that at 25% voltage, with an out-of-phase close, the motor rotor flux linkages may not have decayed sufficiently, and that the transient current and torque associated with the bus transfer or reclosing may not remain within acceptable levels (Beckwith and Yalla [B7]). Additional information is found in 6.4 of IEEE Std C37.96–2012, and in the IEEE Power System Relaying Committee Motor Bus Transfer Report [B34].

For more information, refer to 6.11.

Consensus

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